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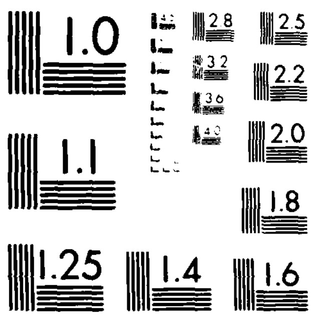

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The Ohio State University

ElectroScience Laboratory

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Seventh Annual Report 710816-17
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June 15, 1984

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This report presents the seventh annual summary of research at Ohio State sponsored by the Joint Services Electronics Program (JSEP). The research is in the area of electromagnetics and the specific topics are: (1) Diffraction Studies; (2) Hybrid Techniques; (3) Integral Equation Studies; (4) Scattering by Penetrable Geometries; and (5) Time Domain Studies.

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Hybrid Techniques	Time Domain	Inverse Scattering	

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DIRECTOR'S OVERVIEW

This report represents the seventh annual summary at the Ohio State University sponsored by the Joint Services Program (JSEP).

It is first observed that this Annual Report is actually a Semi-annual Report in that the Sixth Annual Report was published in December 1983.

This early reporting is being done to place our schedule in accordance with the format given at the JSEP Director's meeting of May 14. Nevertheless, substantial progress has been made in all areas of research. The research is in the area of electromagnetics and under the same general subtopics discussed in the Sixth Annual Report. Twelve graduate students have been involved in this research over the past year. By the close of the current contract period, with the support of JSEP, there should be at least 5 additional students granted Ph.D. degrees and 2 additional students granted M. Sci. degrees this year in Electrical Engineering, making a total of 14 Ph.D. and 12 M. Sci. degrees obtained under JSEP sponsorship.

As may be seen in the Annual Report Index, reprints have been included in the period March 1983 to March 1984. This period was selected to allow time for reprints to become available. There are 6 reprints contained in the Appendix, 10 papers have already been accepted for publication in the coming year and an additional 9 papers are already planned to be written next year.

I. INTRODUCTION

The research is in the area of electromagnetics and the specific topics are: (1) Diffraction Studies; (2) Hybrid Techniques; (3) Integral Equation Studies; (4) Time Domain; and (5) Transient Signature Measurements of Radar Targets for Inverse Scattering Research.

It should be observed that much of the research reported herein is primarily directed toward the last two topics in the JSEP Electromagnetics Priority List for 1984. Specifically we are studying carefully the analysis of electromagnetic waves for lossy penetrable materials in the presence of a conducting surface. It is observed that this is a major undertaking and the effort required to complete it will take a substantial period of time. However, results will be forthcoming on a continuing basis. This is quite similar to the development of the UTD at the ElectroScience Laboratory which has been adopted by a vast number of users. Of course, we are continuing our well known research in the target identification area. Some of the hybrid work will also find further application in the fundamental understanding of coupling into complex structures. Thus, our efforts are already directed toward goals set by the funding agencies. It may be worth observing that we have an interest and substantial background in all the areas listed except for the monolithic integrated wave devices and indeed are actively seeking further support for several of these goals or priorities.

II. DESCRIPTION OF SPECIAL ACCOMPLISHMENTS AND TECHNOLOGY TRANSITION

In the Sixth Annual Report we made the following statements;

> "Our major research area continues to be the analysis of electromagnetic radiation and scattering. Associated with this primary goal is a substantial program for improving our experimental capabilities. This was supported in part by the JSEP program and has expanded recently with other sponsorship so that our anechoic chamber compact scattering range is probably the best of its kind at the present time. This is emphasized by the fact that we have provided information to Scientific Atlanta (the reflector manufacturer) for improving these facilities. We have also been contacted by several other manufacturers requesting assistance in building the next generation of compact ranges. It is noted that the stepped frequency concept originated under JSEP was then developed using the compact range under separate funding by ONR. Additional improvements were made under funding from NASA. This has indeed been a most rewarding area of research."

These statements turn out to be an understatement. We can now report that Scientific Atlanta is incorporating our designs in their compact reflector. In fact, they are donating the first modified compact reflector to the ESL (~ 500K value). We have discussed compact range technology with many organizations including Sandia, Hughes, Rockwell, NASA, Martin Marietta, MacDonald Douglas, SPC, Westinghouse, Motorola, etc. Thus, this work started under JSEP is being rapidly converted to practice by many major industries. Also, there have been further developments funded by various agencies based on this technology initiated originally under JSEP. One of these is rather interesting, i.e., using the compact reflector to simulate ranges from 50 feet to infinity by displacing the feed four feet from the focal point (50 foot range).

Not only has the compact range work extended the state-of-the-art of RCS measurements, but we have also collected a substantial amount of phasor RCS data as a function of aspect, polarization and frequency for a variety of targets. This data is of substantial value to target identification groups both at the ElectroScience Laboratory and elsewhere.

The diffraction studies continue to provide the basis for the extension of our radar scattering analyses of complex objects under other sponsorship. These studies were originally being directed toward generating computer codes for E.M. scattering from bodies of complex shape. However, current security regulations would require a secure computer to make such calculations. Thus, our sponsors are undertaking this role while we continue to provide guidance to this effort.

As we reported last year, computer codes based on the high frequency asymptotic techniques for antennas mounted on various types of vehicles are now used through out the aerospace industry. In fact more than 35 copies of the computer tape containing these codes have been sent to various organizations at their request during the past year. These codes have been declared to be sensitive and now fall under the export control laws.

Computer codes obtained from the integral equation and surface patch modeling studies are also being widely distributed. In the past several years more than 40 copies of this code have distributed.

The basic work conducted under JSEP sponsorship is being used under other sponsorship for the development of these codes. The transfer of technology is being assisted by the distribution of computer codes.

The research involving integral equation solutions for penetrable media has resulted in several technical advances. First, Dr. Newman had incorporated polarization currents to represent a dielectric slab in the presence of a conducting edge. By using the Green's function for the half plane he has been able to eliminate computational problems associated with the edge singularity.

There is a continued concentrated effort to develop asymptotic techniques for treatment of penetrable bodies in addition to our continued research on asymptotic solutions for conducting bodies.

The work on hybrid solutions is continuing. A result of this effort in the past year has been the study of scattering from cracks. Problems being attacked by this approach include: 1) diffraction involving special edges, 2) diffraction between edges and dielectric boundaries, 3) coupling by apertures, 4) analysis of microstrip antennas, and 5) reflector antenna synthesis.

Professor Richmond, under the study of Scattering by Penetrable Geometries, has shown that he can represent a rather large thin flat dielectric sheet by only three unknowns. This work properly extended will make the new so called "physical basis" technique a standard analysis, available for many applications and avoid the problem of treating huge matrices. Both of these studies will not only provide check cases and guidance for the asymptotic cases already discussed but will become a design tool for any case where a thin penetrable layer ($< 0, 2\lambda$ thick) is used.

A JSEP paper by Professors Kennaugh and Moffatt is being used as the lead paper in the Proc. of NATO Advanced Research Workshop on Inverse Methods in Electromagnetic Imaging. The entire workshop is dedicated to the memory of Professor Kennaugh, who (along with Professor Moffatt) was a major contributor to our JSEP activities in this important area of research.

There has been substantial progress in the general area of time domain measurements and target identification. Remarkable improvement has been achieved in obtaining the impulse response of a cone-cylinder simply by replacing the sphere with a circular disk as a calibration taret. The problem, that was eliminated, was caused by the isotropic scattering nature of the sphere. The resulting time domain pattern is in excellent agreement with predictions.

A method of combining low frequency calculated or measured scattering data with high frequency asymptotic computations has been demonstrated for the case of a cavity-type tartet. Frequencies in the vicinity of low or first cutoff are spanned using rational function approximants.

Certain K-pulse waveform results for finite non-uniform transmission lines, first produced by Professor Emeritus E.M. Kennaugh, have been duplicated. This indicates our basic programs are correctly interpreting aspects of the K-pulse concept. The K-pulse, correctly interpreted, provides a very fundamental insight into the inverse scattering problem.

Finally it is observed that the prediction - correlation target recognition procedure developed under JSEP sponsorship is now being extensively tested on a large noncooperative target recognition program. Procedures for complex natural resonance extraction from measured scattering data also developed under JSEP sponsorship are being utilized on other programs.

The impulse reponse concepts, while not initially developed on JSEP, has been continuously refined on this program. It is now generally recognized in the electromagnetics area that broadband scattering or radiation data are most easily interpreted in the time domain. Thus, target recognition, radar cross section control and scattering mechanisms analysis all are utilizing time domain waveforms. Data from broadband compact reflectivity measurement ranges are used to produce complete time-dependent polarization scattering matrices.

III. RESEARCH SUMMARY

A. Diffraction Studies

Researchers: R.G. Kouyoumjian, Professor (Phone: (614) 422-7302)

P.H. Pathak, Assistant Professor

N. Wang, Senior Research Associate

R. Tiberio, Visiting Professor and Consultant

R. Paknys, Graduate Research Associate

M. Buyukdura, Graduate Research Associate

R. Rojas, Graduate Research Associate

Accomplishments

During the present contract period, the work accomplished in extending the uniform geometrical theory of diffraction (UTD) has been substantial. This research, and the technical papers based on this research which have recently appeared (or have been accepted for publication) are described below.

1. Diffraction by Non-Conducting Surfaces

a. Smooth dielectric covered and impedance convex surface

The mutual coupling between antennas mounted on a conducting surface covered with a layer of dielectric material is of interest in many microwave applications. One application cited in the JSEP priority list for 1984 is that of conformal arrays. Work has been in progress to study the surface impedance model of the dielectric-coated surface. It is known that the surface-impedance model provides a convenient and useful tool to examine the electromagnetic characteristics of the surface waves associated with the dielectric-coated surface. It has been reported in the sixth annual JSEP report that some preliminary results for the dominant one-ray contribution to the surface field, produced by a magnetic line source located on a circular impedance cylinder, were obtained. Figures A-1 through A-6 present the numerical results of the one-ray solution G_∞;

$$G_\infty = \frac{-1}{2\pi\kappa\alpha} \int_{-\infty}^{\infty} \frac{H_\mu^{(2)}(ka)}{H_\mu^{(2)'}(ka)\ j\bar{C}H_\mu^{(2)}(ka)} e^{-j\mu\phi} d\mu$$

for a circular cylinder as a function of radius ka and surface impedance $\bar{C} = jX_s$. In Figures A-1 through A-6, $\xi = m\phi$, $m = (\frac{ka}{2})^{1/3}$, $T = a\phi$, and ϕ is the angular separation between the source and the observer. Notice that with an increase in the value of the inductive impedance X_s, the surface field intensity increases in the shadow region as a result of stronger trapping of the surface waves. It should be pointed out that the results presented in Figures A-1 through A-6 are obtained by manipulating various alternative representations of the Green's functions associated with a circular impedance cylinder. This approach avoids the tedious numerical integration procedure needed for evaluating the integral representation for the quantity G_∞. In the deep shadow region, G_∞ can be evaluated by a different procedure, namely, the residue theorem. This second approach has also been employed to obtain numerical results for G_∞, and excellent agreement is obtained when the numerical results obtained by two different methods are compared in the deep shadow region.

In order for this solution to be useful, the high frequency characteristics of the one-ray solution has to be examined. This task has been performed during the present research period. Based on a high frequency study of the surface field solution for the perfectly-conducting circular cylinder, it is found that a similar transition function $v(\xi,q)$, $q = jm\overline{C}$, could be introduced for the circular cylinder with a constant surface impedance. This transition function $v(\xi,q)$ could be interpreted as a correction factor to the surface field solution obtained for the perfectly conducting planar surface. That is, the function $v(\xi,q)$ takes into account the effects of curvature and the surface impedance of the curved surface. Note that, for $q = 0$, the transition function reduces to the well known transition function $v(\xi)$ for a perfectly conducting convex cylinder. Some numerical results are presented in Figures A-7 through A-9 for the transition function $v(\xi,q)$, using ka as a parameter, for various value of q. The function $v(\xi,q)$ is obtained via the following expression

$$G_{\infty} \triangleq \frac{-j}{2} H_0^{(2)}(kt)\ v(\xi,q)$$

where

$$\xi = m\phi \text{ and } kt = ka\phi.$$

Note that the above expression for $v(\xi,q)$ is employed based on an observation made on the solution for a perfectly conducting circular cylinder.

It can be seen from Figures A-7 through A-9, that as the frequency increases, the transition function $v(\xi,q)$ tends to approach an upper bound. This is of great interest in that a high frequency "universal" transition function which is independent of ka could be deduced from the analysis. As an example, using ka = 40, q = 0.5, a transition function $v(\xi,q)$ is obtained. This function $v_{40}(\xi,q)$ is then employed as the high frequency universal transition function for circular cylinder with q = 0.5. Figure A-10 presents the numerical results for the surface fields due to a magnetic line source radiating from a circular cylinder with parameters q = 0.5. It is observed that excellent agreement is obtained between the eigenfunction solution and the high frequency GTD solution. It should be pointed out that in Figure A-10, the (residue) creeping wave solution fails in the region close to the source, while the transition function $v(\xi,q)$ yields the correct results.

In the case of a thick layer of dielectric material covering the circular cylinder, the simple surface impedance model is no longer valid. Furthermore, under certain conditions, higher order modes of surface waves could be supported by the coated surface. The investigation on the topic of mutual coupling between antennas on a circular cylinder with a dielectric coating will be performed in the coming year. Relationship between the coated surface and the surface impedance approximation will also be studied.

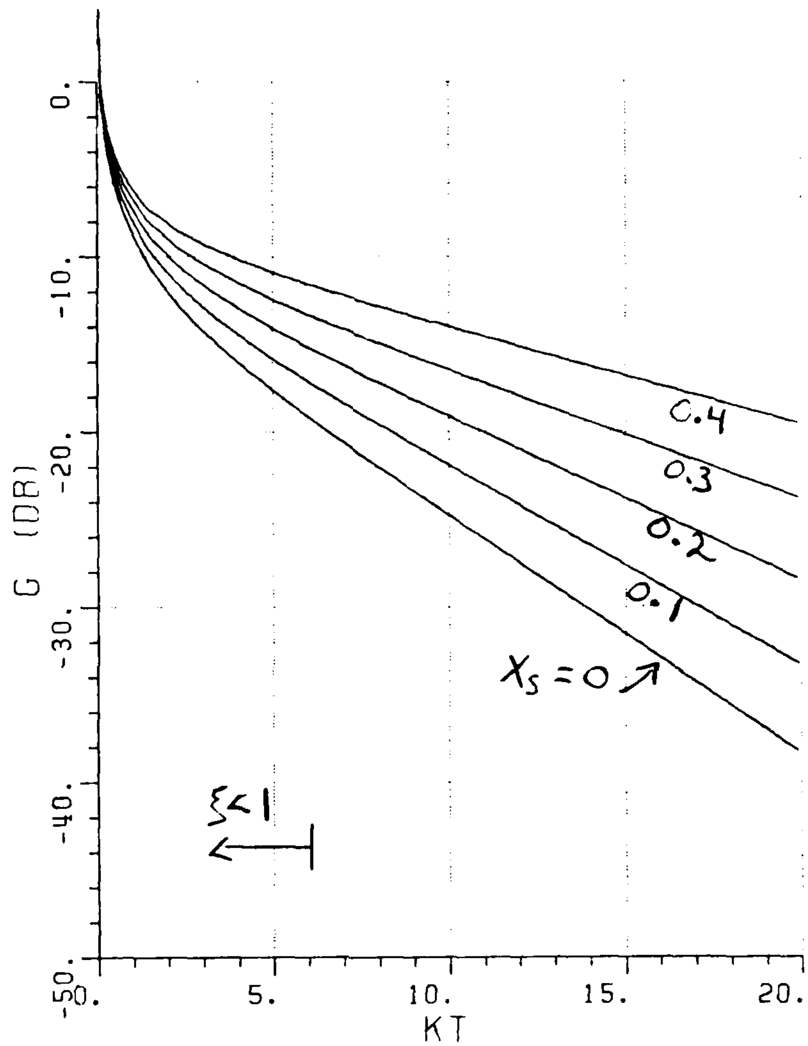

Figure A-1. Surface ray G_∞ for ka=10, showing the effect of varying the surface impedanace $\bar{C}=jX_s$.

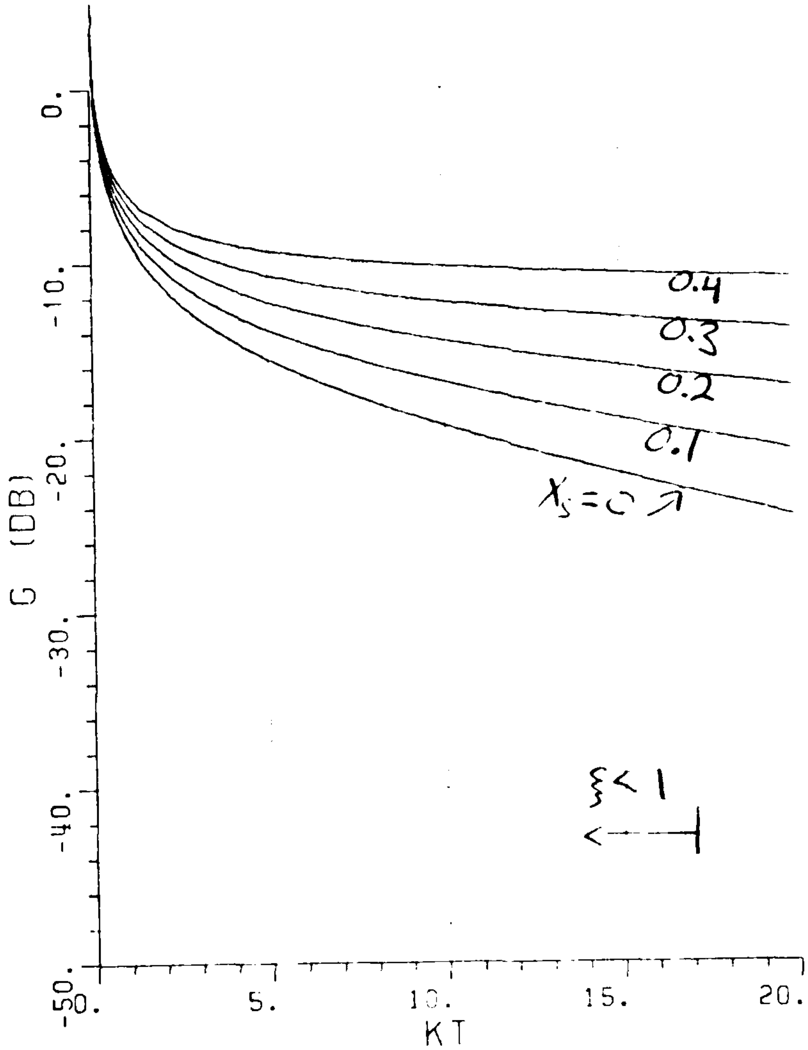

Figure A-2. Surface ray G_∞ for ka=50, showing the effect of varying the surface impedance $\overline{C}=jX_s$.

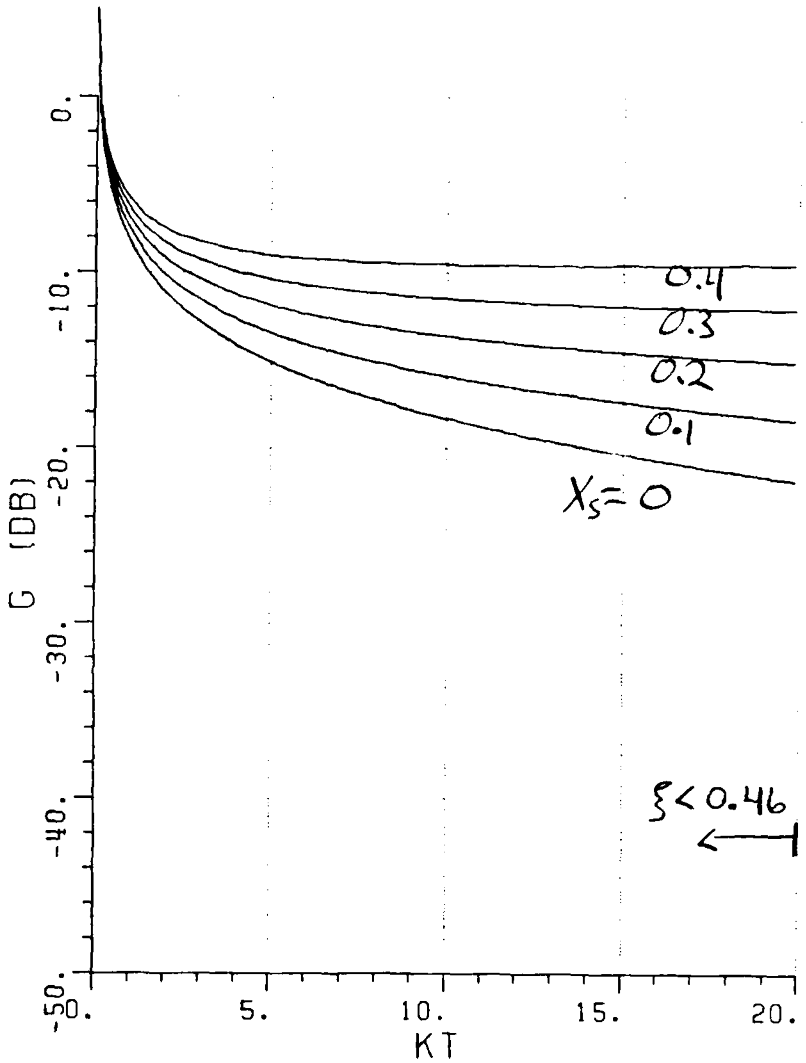

Figure A-3. Surface ray G_∞ for ka=200, showing the effect of varying the surface impedance $\overline{\tau}=jX_s$.

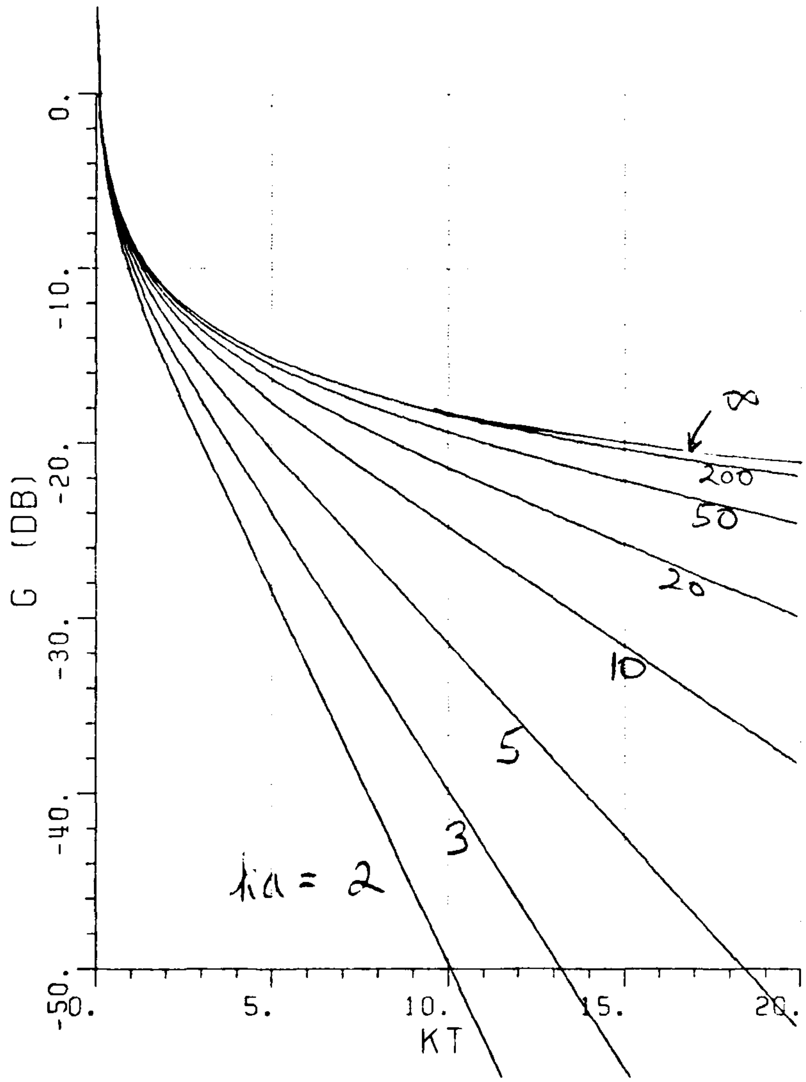

Figure A-4. Surface ray G_∞ for a perfectly conducting cylinder ($\bar{C}=0$) showing the effect of varying ka.

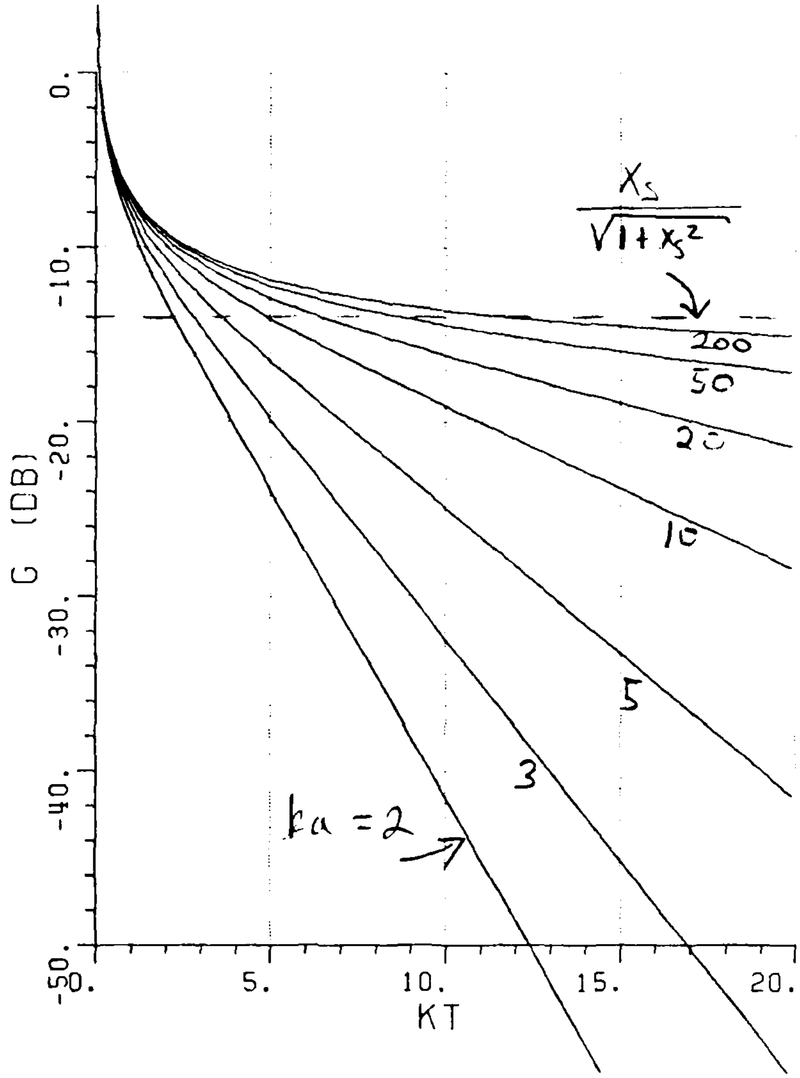

Figure A-5. Surface ray G_∞ for $\bar{C}$=j0.2, showing the effect of varying the cylinder radius ka.

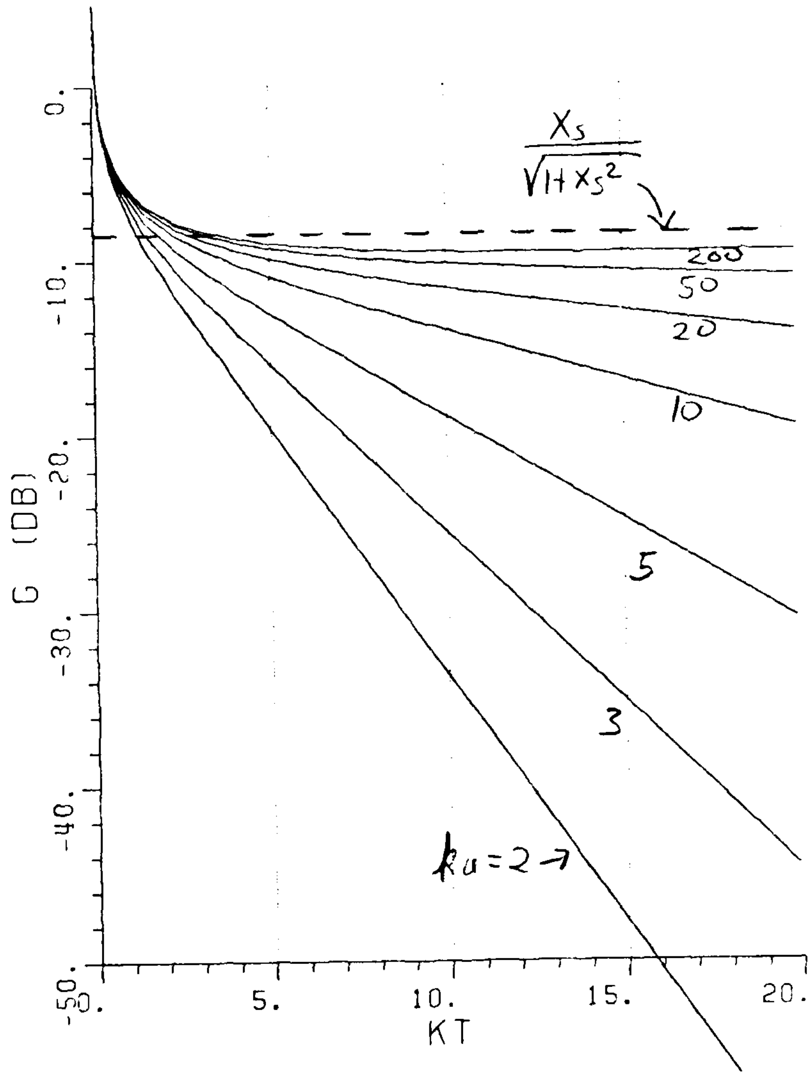

Figure A-6. Surface ray G_∞ for $\bar{C}$=j0.4, showing the effect of varying the cylinder radius ka.

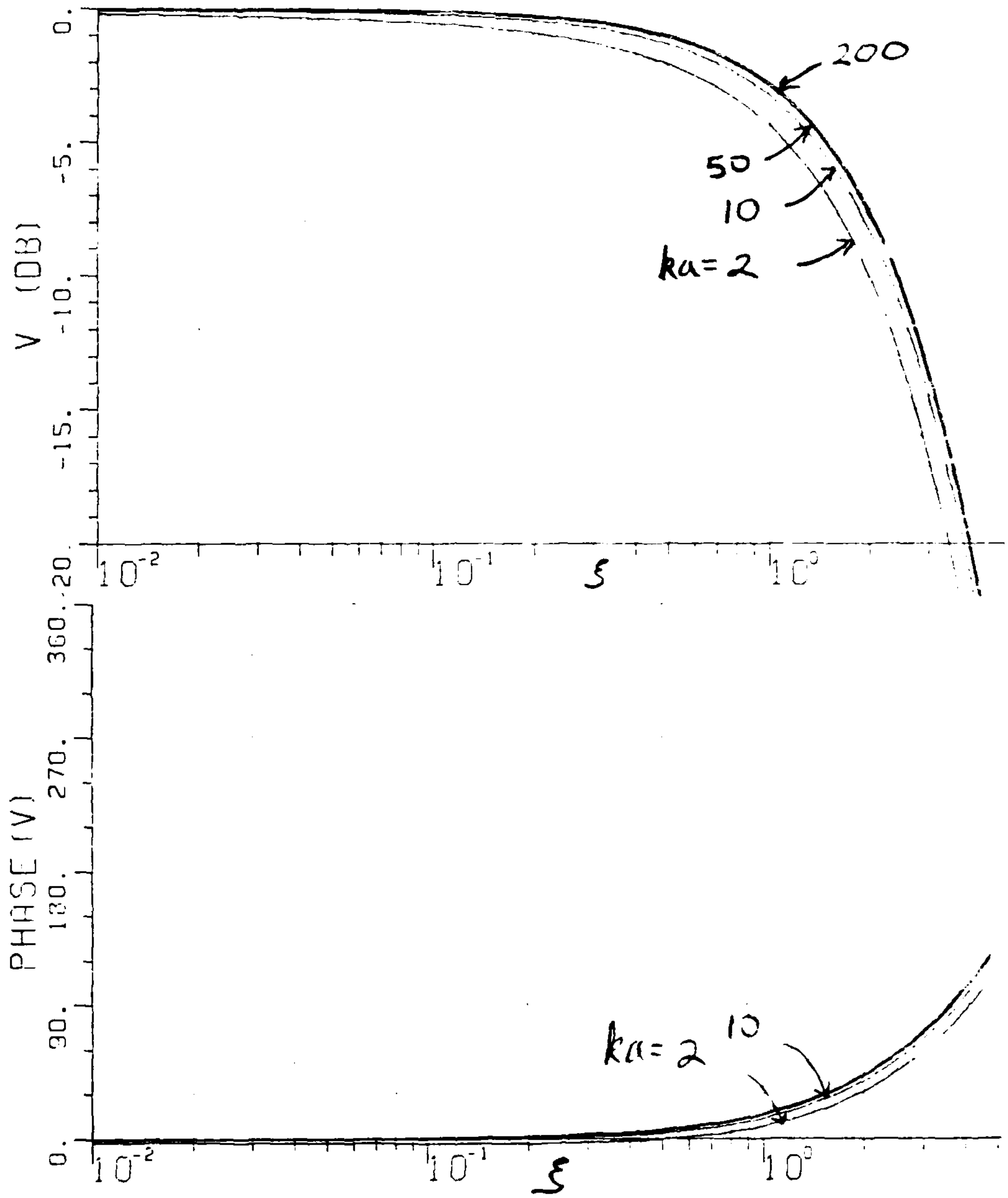

Figure A-7. Transition function $v(\xi,q)$ for a perfectly conducting cylinder ($q=0$) showing the dependence on ka.

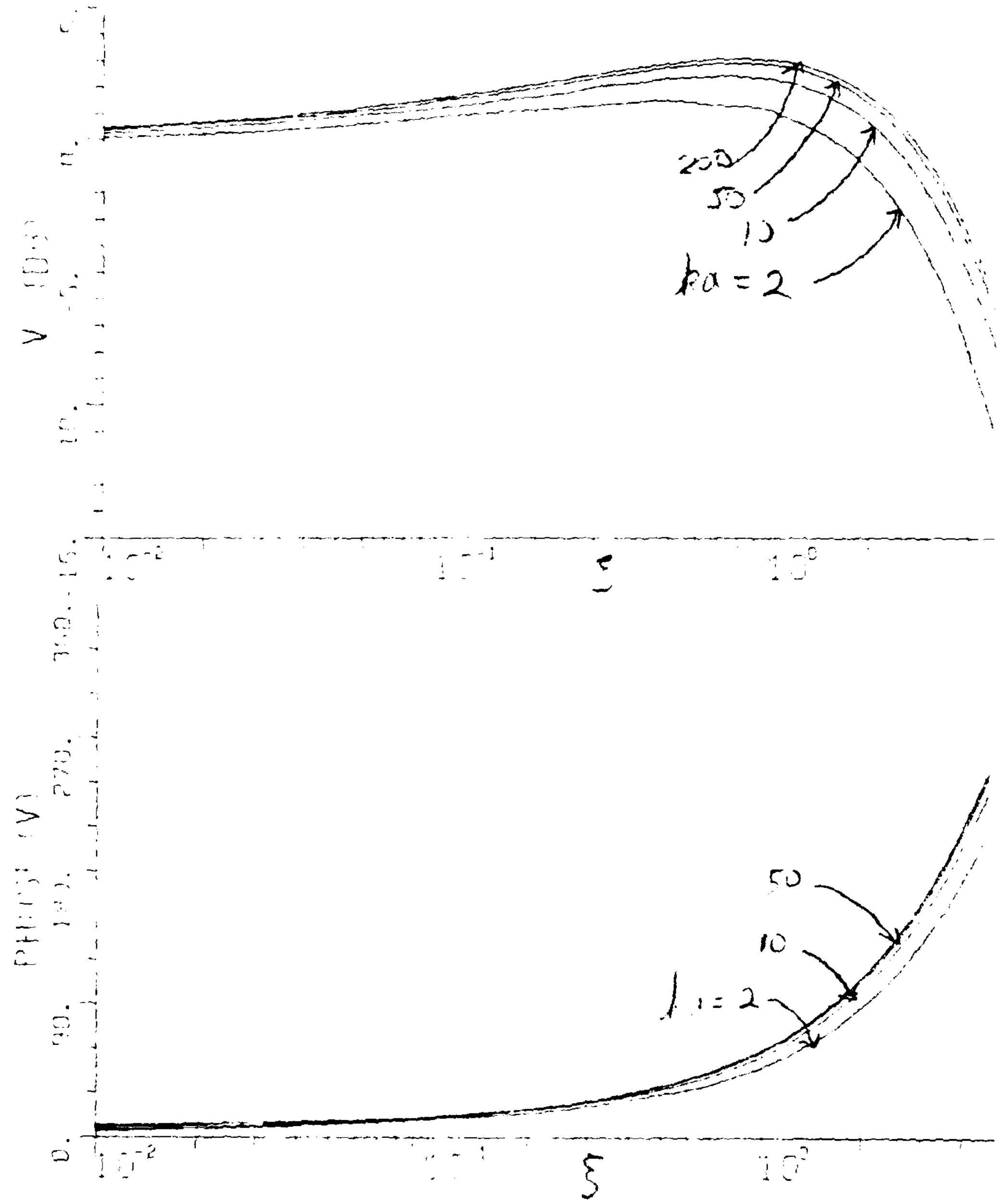

Figure A-8. Transition function v(ξ,q) for a=0.5 showing the dependence on ka.

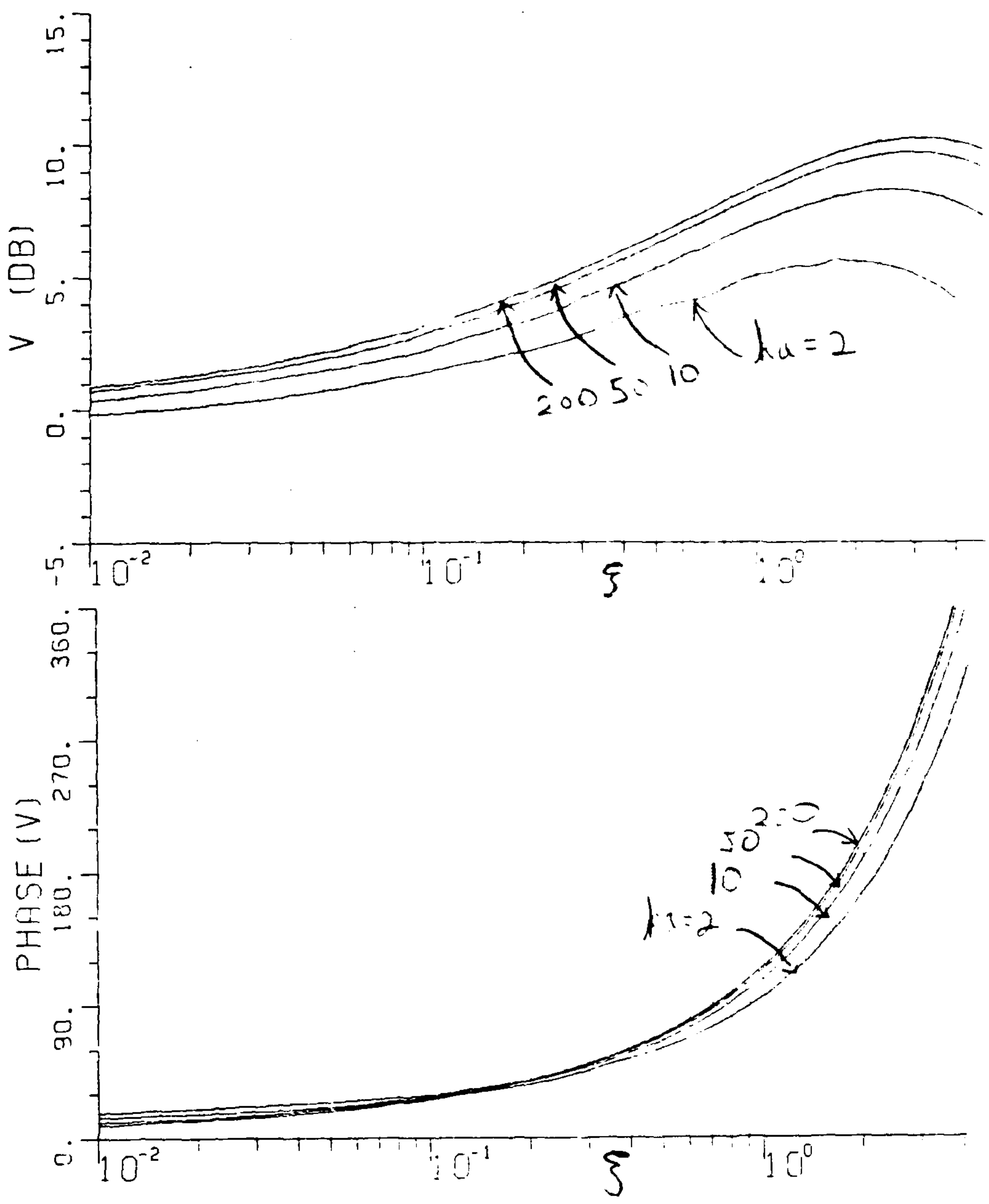

Figure A-9. Transition function $v(\xi,q)$ for q=1.0 showing the dependence on ka.

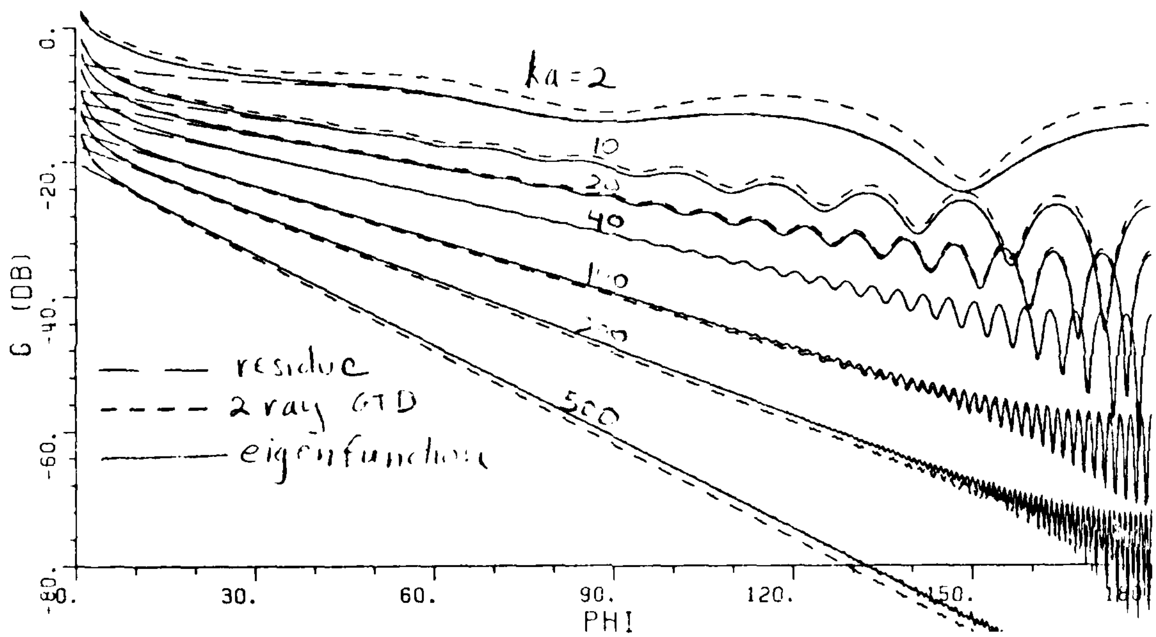

Figure A-10. Surface fields due to a magnetic line radiating on a circular cylinder with radius ka and q=0.5.

The following papers are to be prepared for publication:

1. "Electromagnetic scattering from a dielectric-coated cylinder", N. Wang.

2. "Radiation from a convex reactive surface", N. Wang.

3. "Surface ray solution for the surface fields on a curved reactive surface", J.R.J. Paknys and N. Wang.

b. Discontinuity of surface impedance

The problems of EM scattering by discontinuities in surface impedance arise not only in the control of the RCS of perfectly conducting structures by impedance loading, but they also arise, for example, in the design of flush mounted aircraft/missile antennas with a thin coating (or a radome), of finite extent, and in the studies for improving the isolation among a pair of flush mounted antennas by placing an absorber (which can be modeled by a lossy impedance surface) in between those two antennas.

A problem of interest in the area of EM scattering is that of plane wave diffraction by a strip with two face impedance (i.e., the impedance on the two sides of the strip can, in general, be different). This problem has been analyzed for the special case of grazing incidence; the analysis for illumination at aspects away from grazing on the strip is actually simpler than the case of grazing incidence. It is noted that the analysis in the forward scatter direction for grazing incidence is complicated because the diffraction from the leading edge produces a non-ray optical field near the trailing edge; consequently, the diffraction from the trailing edge cannot be handled directly by ray methods. Here, the diffraction of the non-ray optical field is analyzed via a spectral extension of the geometrical theory of diffraction. A paper has been written recently which describes this work; namely:

"Scattering by a Strip with Two Face Impedances at Edge-On Incidence", by R. Tiberio, F. Bessi, G. Manara, and G. Pelosi, accepted for publication in J. Radio Science.

The geometrical theory of diffraction solution employed in the above analysis (which is formulated in the spectral domain) is based on the work of Maliuzhinets [1]. The result for the diffraction coefficient available from Maliuzhinets' work, dealing with the problem of the diffraction of a plane wave by a wedge with two face impedances, is non-uniform. Consequently, Maliuzhinets' results had to be modified here so that it would remain uniformly valid across the geometrical optics incident and reflection shadow boundaries formed by the edge of the wedge.

A second configuration of interest which has also been investigated recently, and which is somewhat related to the previous one, deals with the problem of the diffraction of an EM plane wave by the edges of an impedance surface patch on a planar perfectly-conducting boundary of infinite extent. In this investigation, an asymptotic high frequency solution for the surface field is obtained again using the spectral theory in conjunction with a uniform version of Maliuzhinets result [1]. Both the TE and TM polarizations are considered in this two-dimensional problem, and the contribution from the bound surface waves (on the impedance surface) is included in the solution. In addition, this analysis is further extended to treat the diffraction by a planar three-part impedance surface. A paper describing this work has been written recently, namely:

"High Frequency Scattering From the Edges of Impedance Discontinuities on a Flat Plane", by R. Tibereo and G. Pelosi, IEEE Transactions on Antennas and Propagation, Vol. AP-31, No. 4, pp. 590-596, July 1983.

Also, work has been completed on the analysis of the scattering of EM plane and surface waves by a planar, two part surface in which one part is a perfect electric or magnetic conductor and the other part is characterized by a non-zero surface impedance. This two-dimensional analysis is based on the Wiener-Hopf procedure together with Weinstein's method of factorization [2]. These Wiener-Hopf based solutions, which have been obtained for both the TE and TM polarizations, provide uniform (GTD) diffraction coefficients for the discontinuity in surface impedance; furthermore, they constitute solutions to canonical problems which are crucial to the development of a uniform GTD analysis for the problems of the diffraction by the edge of a thin dielectric or ferrite half plane, and by the edge of a thin dielectric or ferrite half plane on a perfectly conducting surface. The problem of the diffraction by a thin dielectric or ferrite half plane is discussed later in part c.

An analysis of the high frequency EM radiation by a magnetic line (or line dipole) source on a uniform impedance surface which partially covers a smooth perfectly-conducting convex surface has been performed in the past. A manuscript describing this work,

> "An Approximate Asymptotic Analysis of the Radiation from Sources on Perfectly-Conducting Convex Cylinders with an Impedance Surface patch", by L. Ersoy and P.H. Pathak,

has nearly been completed. The preceding work is of interest, for example, in the study of fuselage mounted airborne slot antennas with a finite dielectric cover for the purposes of controlling the field radiated near the horizon (or shadow boundary) over that in the absence of the cover. The impedance surface approximation can be employed here to model the dielectric patch or covering if the dielectric is sufficiently thin.

The work on the diffraction problems described above, dealing with structures possessing a discontinuity in surface impedance, will be continued in the future phases of this study in order to extend these solutions to treat more general situations (e.g., to treat 3-D problems).

c. Diffraction by the edge of a thin dielectric or ferrite half plane

The diffraction by a thin dielectric or ferrite half plane is an important canonical problem in the study of the diffraction of electromagnetic waves by penetrable bodies with edges. The excitation chosen for studying this problem is either an electromagnetic plane wave, or a surface wave (incident along the dielectric/ferrite surface); both types of excitation are considered. The present analysis of the dielectric/ferrite half plane diffraction problem begins by bisecting the semi-infinite dielectric/ferrite half plane by an electric wall in the first case, and by a magnetic wall in the second case. The problem of plane (or surface) wave diffraction by the dielectric/ferrite half plane is then constructed by appropriately superimposing the corresponding solutions for the electric and magnetic wall bisections, respectively. For sufficiently thin dielectric and ferrite half planes, one can employ canonical solutions based on the Wiener-Hopf technique in which one approximates the effect of the thin dielectric or ferrite slab by an equivalent impedance boundary condition; these canonical solutions can be modified by semi heuristic physical arguments to then treat moderately thick dielectric or ferrite half planes. The Wiener Hopf solutions to the latter canonical problems dealing with the two part impedance surface were mentioned briefly in the previous part (b) dealing with discontinuities in surface impedance.

The above procedure is expected to yield a dielectric half-plane diffraction coefficient which is more accurate than the one obtained by Anderson for the case of an incident electric plane wave field which is parallel to the edge of the thin dielectric half plane [3], because the latter analysis employs an approximate "equivalent" polarization current sheet model for the thin dielectric half plane. The approximation in [3] contains only a part of the information present in the more general approach being employed in our work; consequently, it is found that the previous analysis in [3] yields a diffraction coefficient which is valid only for an extremely thin dielectric half plane. Furthermore, the equivalent polarization current approximation leads to a rather complicated Wiener-Hopf analysis when the magnetic field is parallel to the edge; the latter case has not been treated by Anderson [3].

At the present time, the diffraction coefficients for the two-dimensional case of both TE and TM plane and surface wave excitation of the thin dielectric and ferrite half-planes have been obtained, and they have been tested for accuracy in the dielectric case. Also, these results have been extended to treat a moderately thick dielectric or ferrite half plane which is excited not only by plane and surface wave fields, but also by a cylindrical wave (or line source excited) field. The thickness of the half plane is allowed to be such that only the first TE and TM surface wave can exist. The Uniform GTD (UTD) solution obtained for the thin dielectric or ferrite half plane suggests an ansatz based on a semi-heuristic physical argument, as indicated earlier, which allows one to perform the extensions to treat the moderately thick dielectric or ferrite half plane, and also to treat the case of cylindrical wave illumination. In addition to extending the 2-D analysis to treat moderately thick dielectric and ferrite half planes, work has also been completed to include loss in the dielectric and ferrite half planes. The final result for the lossy case is almost as simple to use as the lossless case.

A typical numerical result for the diffraction of a cylindrical wave by a moderately thick dielectric strip that is based on the present UTD solution is shown in Figure A-11. The UTD based result in Figure A-11 is compared with an independent numerical moment-method solution of an integral equation pertaining to this line source excited lossy dielectric strip geometry. Since the line source illuminates the strip near grazing angles of incidence in Figure A-11, it is especially important in this near grazing incidence case to include surface wave diffraction effects as well. The contribution of all the dominant singly and multiply diffracted rays is included for calculating the pattern in Figure A-11. It is noted from the pattern in Figure A-11 that the total UTD field is continuous at the reflection and

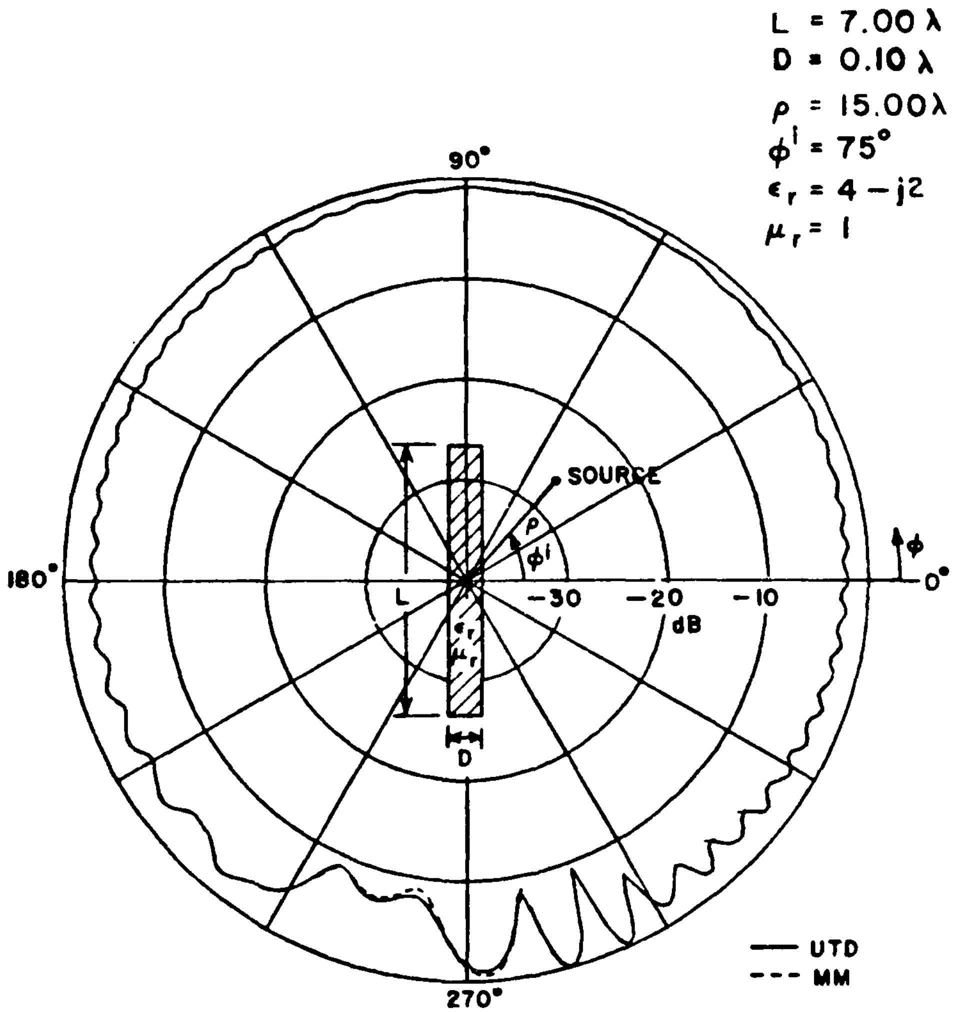

Figure A-11a. Far zone pattern of an electric line source in the near zone of a lossy dielectric strip.

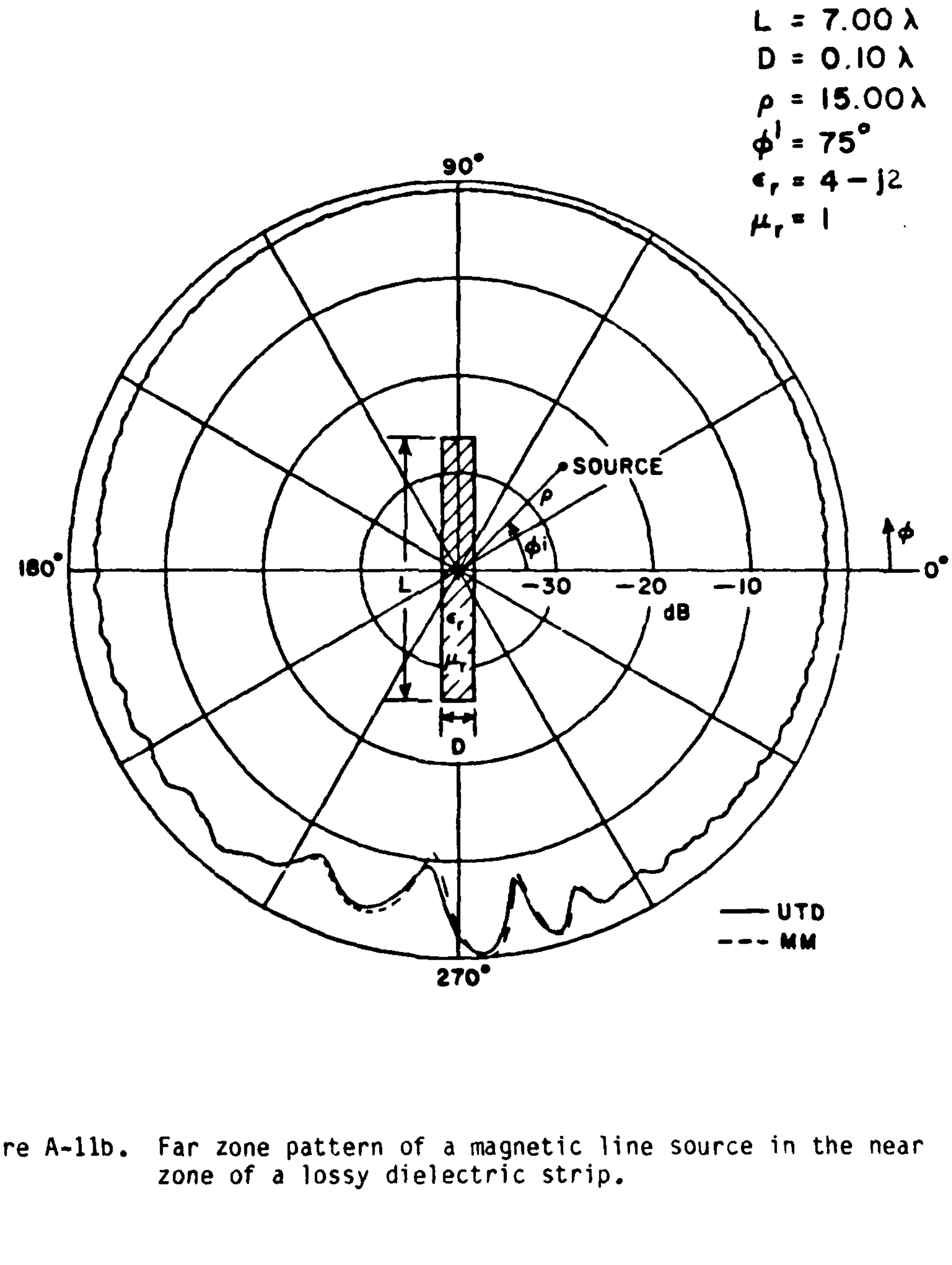

Figure A-11b. Far zone pattern of a magnetic line source in the near zone of a lossy dielectric strip.

transmission shadow boundaries as it should be; furthermore, the very close agreement between the totally independent UTD and moment-method solution in Figure A-11 (and also in other cases which are not shown here) is indeed gratifying. The effects of surface wave diffraction become more pronounced in the lossless case.

Work is currently in progress to treat the three-dimensional (3-D) problems of the diffraction of obliquely incident plane, conical, and spherical waves, and obliquely incident surface waves by a thin (or at most moderately thick) dielectric half-plane. These important generalizations are not trivial because an obliquely incident plane wave is expected to launch both TE and TM type surface waves at the edge of the dielectric half plane. In other words, mode coupling between TE and TM surface waves obliquely incident on the edge of a dielectric half plane is possible. Consequently, the generalization of the two-dimensional (2-D) solutions to treat the corresponding three-dimensional (3-D) problems is not straightforward. It is also noted that even though a relationship exists between the 2-D and 3-D solutions, this is not a direct relationship of the type which would allow the 3-D solutions to be constructed in a simple way from the 2-D solutions as is possible for the case of a perfectly conducting half plane. Besides being useful in analyzing antenna and scattering problems, the 3-D dielectric half plane diffraction solution may also be of interest in the area of integrated optics and millimeter wave integrated circuits where open dielectric guiding structures are employed.

2. Diffraction by Perfectly-Conducting Surfaces

a. Vertex diffraction

The analysis of vertex diffraction is important because one frequently encounters situations where an antenna radiates in the presence of planar structures with edges which terminate in a vertex (or corner). Also, flat plates with edges are used to model aircraft wings and vertical or horizontal stabalizers for calculating the patterns of antennas on aircraft. In these problems, the antenna pattern is affected both by edge diffraction and by the diffraction at the vertices.

A typical vertex in a planar, perfectly-conducting surface is shown in Figure A-12. A more general vertex in a planar surface is formed by the intersection of two otherwise smooth, curved edges. The angle α is the internal angle formed by the tangents to each of the curved edges at the vertex.

The asymptotic high-frequency analysis of electromagnetic vertex diffraction is rather complicated. Vertices not only shadow the incident field, but they also shadow the edge diffracted fields. The shadow boundary of an edge diffracted field is a conical surface whose tip coincides with the vertex and whose axis is an extension of the shadowed edge. The vertex introduces a diffracted ray which penetrates the shadow regions; moreover, the vertex diffracted field must also compensate the discontinuties in the incident and edge diffracted

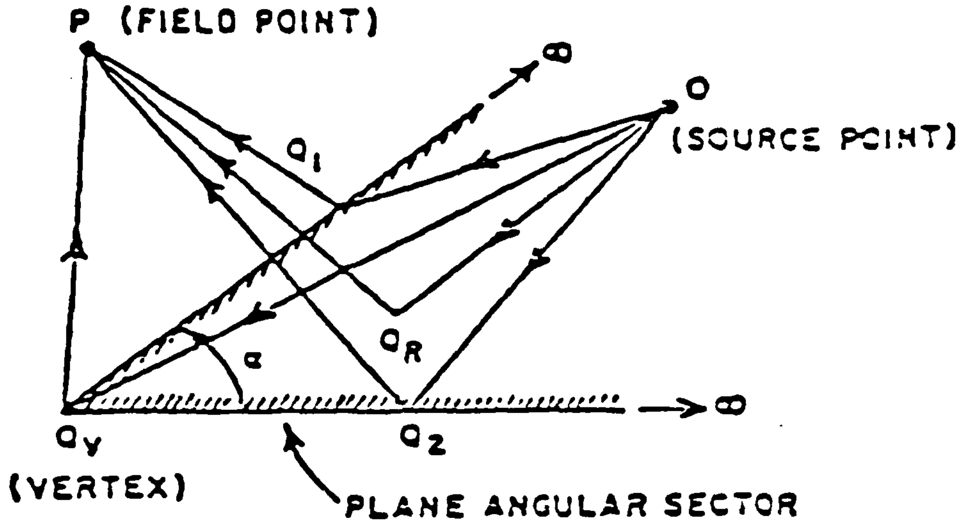

Figure A-12. Various rays associated with the reflection and diffraction by a plane angular sector.

fields at their shadow boundaries. At these boundaries the vertex diffracted field assumes its largest magnitude and, hence, its greatest importance. If the vertex diffracted field is omitted in the GTD solution, then substantial discontinuities connected with the shadowing of the incident and edge diffracted fields may occur in the calculated radiation pattern.

A simple, approximate vertex diffraction coefficient which appears to work reasonably well in certain cases has been obtained at the ElectroScience Laboratory [4,5]. However, this result has been found heuristically using a combination of theory and experiment; it therefore needs to be improved in order to be useful in the general situations encountered in practice. Nevertheless, this diffraction coefficient offers some clues for constructing the more refined and useful vertex diffraction coefficient, which we expect to obtain from asymptotic analysis.

The objective of this research is a uniform asymptotic solution for the electromagnetic field scattered by the vertex, which can be interpreted ray optically in terms of contributions from the critical points Q_R, Q_1, Q_2 and Q_V. The approach is to approximate the current away from the edges by the geometrical optics current. Near the edges, but away from the vertex, the local half-plane current is used and near the vertex the first few terms of the eigenfunction solution [6] are employed. The integral representation of the field radiated by these currents is then approximated by the stationary phase method to obtain the fields diffracted and reflected from the critical points.

Recently a method for asymptotically evaluating the field of the current near an edge was investigated; an eigenfunction representation of the edge current was used. The preliminary results are encouraging and we are pursuing this approach of directly using the behavior of the current near the edge to determine the high-frequency diffracted field. If the method is successful, it will be applied to the eigenfunction representation of the current near the vertex to obtain the vertex diffraction coefficient.

The confluence of the critical points has been examined using the geometrical optics current everywhere on the vertex.
When all the critical points are close to each other, the expression

obtained for the transition function is so complicated it does not appear to be useful. An effort is being made to simplify this expression, and there has been some recent progress in this work.

As was mentioned earlier, a convergent (eigenfunction) solution is needed to represent the current near the vertex. Also, a convergent solution is of great value in numerically checking the approximate high-frequency solutions obtained by asymptotic methods. Therefore, an effort has been made to accurately determine the dyadic Green's function for the plane angular sector.

To find the dyadic Green's function we begin by expanding it in terms of a complete set of vector wave functions which are solutions of the vector wave equation along with the radiation condition and the boundary conditions on the surface containing the vertex. The vector wave functions, in turn, are expressed in terms of scalar wave functions which are solutions to the scalar wave equation with the appropriate boundary conditions. Both Neumann and Dirichlet type boundary conditions must be satisfied to yield a complete set of vector wave functions. The final step of the solution involves separating the scalar wave equation in the sphero-conal coordinate system. The resulting separated equations include the spherical Bessel equation and two Lame' equations (one with periodic boundary conditions and the other with nonperiodic ones) which are coupled through the two eigenvalues which are actually the separation constants. It is precisely these eigenvalue pairs which serve as the summation index of the dyadic Green's function.

The solution is thus ultimately reduced to solving for the eigen-values and eigenfunctions of the separated Lame' equations. It is then a straightforward procedure to construct the vector wave functions and hence the dyadic Green's function. Once this is found one can proceed to investigate a wide variety of problems because of the versatility and general nature of the Green's function solution.

There is no known closed form solution to the Lame' equations and one is therefore attracted to an infinite series solution. Earlier work [6] used Fourier sine and cosine series representations, but these resulted in the need to solve two simultaneous, infinite continued-fraction equations for the eigenvalues and eigenvectors. This solution proves to be numerically formidable, and indeed, almost impossible for higher order eigenvalues because of the rapidly varying nature of the continued fractions. However, Sahalos has used these representations [7] and reports that he has developed methods of calculation which are more efficient and accurate. We plan to study his method before doing further work on this problem; it may be adequate for purpose of calculating the dyadic Green's function for the plane angular sector.

When the sector angle $\alpha = \pi$, the dyadic Green's function for the plane angular sector provides a useful solution for the diffraction by a half plane. This is discussed in the next section.

b. Paraxial diffraction

i) At edges

As was mentioned in the last section, the dyadic Green's function for the plane angular sector can be applied to the half-plane by letting the sector angle go to 180°. The Lame' differential equations decouple and the eigenvalues and eigenfunctions are easily found; furthermore, this solution can be extended to the wedge without difficulty. The advantage of this spherical wave solution for the dyadic Green's function of the wedge over that given in [8] is that it can be used when the field and the source point are close to the edge. This should make it possible to extend the UTD solution to the paraxial region, i.e., to grazing incidence on the edge, and to study the propagation of edge waves. These waves are important in analyzing the scattering from plates illuminated at or near grazing incidence or in treating the coupling between monopoles or slots near the edge of a wedge.

A paper has been written on the spherical wave representation of the dyadic Green's function for the perfectly-conducting wedge [9]; its use to determine the fields in the paraxial region is also described in this paper. A summary of the paper was presented at the 1983 International URSI Symposium [10].

The use of this dyadic Green's function to treat the scattering from an object at the edge of the wedge was described in the two preceding annual reports, again the paraxial region is of special interest. A generalization of the T-Matrix method was proposed for non-spherical objects. The method was tested by choosing a sphere whose center is displaced along the edge from the origin of the coordinate system. This simulates the difficulties encountered in treating a non-spherical scatterer. Echo area curves calculated by this method are found to be in excellent agreement with those calculated from an (exact) eigenfunction solution. During the period covered by this report calculations were made of the electromagnetic backscatter from small oblate and prolate spheroids positioned at the edge of a wedge.

Recently this generalization of the T-Matrix method has been extended to the case where there are two or more scatterers positioned at the edge of a wedge. Two methods have been developed for treating this multiple scattering problem. One method is restricted to very small scatterers where the maximum dimension is less than say 0.05λ. It is based on the self-consistent field method and employes the edge guided wave, whose behavior near the edge is independent of the source orientation. The second method is a formal T-Matrix approach to the multiple scattering problem. Scatterer interaction is not restricted to edge waves, i.e., higher order terms are included; hence larger scatterers can be treated using this method. The solution obtained by the second method does not appear to reduce to that obtained by first method as the scatterer size diminishes. Hence the validity of the two solutions may be checked numerically in the case of very small scatterers; we plan to do this.

ii) At smooth, quasi-cylindrical surfaces

Several papers were written (under the JSEP program) and published [11,12,13] which describe Uniform GTD (UTD) solutions for the diffraction by perfectly-conducting convex surfaces. In particular, efficient UTD solutions for the problems of the radiation from sources both off and on a convex surface and the mutual coupling between sources on a convex surface were presented in [11,12,13]. These UTD solutions, for the problems of scattering, radiation, and mutual coupling, which are associated with the radiation by antennas in the presence of an arbitrary, smooth perfectly-conducting convex surface, represent an important and useful contribution to the area of ray methods for analyzing the EM radiation and scattering from complex structures. It is noted that the effects of surface ray torsion on the diffracted fields are explicitly identified in these solutions. Here, the diffracted fields are associated with surface rays as well as with rays shed from the surface rays. It is noted that these surface rays on a convex surface traverse geodesic paths which in general are torsional; i.e., the surface ray paths are twisted (or they do not lie in a plane).

While the above mentioned UTD solutions for sources on or off a smooth perfectly-conducting convex surface are valid under very general conditions, they must be modified within the paraxial regions. For example, these solutions must be modified for an observation point (either on or off the surface) which lies in the paraxial region of an elongated or cigar shaped (quasi-cylindrical) convex surface whenever the rays from the source to that observation point traverse paths which lie within the paraxial zone. At the present time, the solution for the surface fields of a source on the convex surface in [13] has been extended so as to include higher order terms which improve the accuracy within the paraxial region of quasi-cylindrical, or elongated convex surfaces. This surface field (or mutual coupling related) solution provides the electric current density which is induced by a source on the same surface. Such a surface current density can be incorporated into the usual radiation integral to find the field radiated by this current; that step has also been performed presently. Thus, the field radiated by the source on the surface has been obtained via an asymptotic high frequency evaluation of the radiation integral containing this surface current density which remains valid in the paraxial zone. The asymptotic evaluation of this radiation integral associated with a general convex surface has been done carefully in order to obtain a simple and useful uniform solution for the radiated field which not only remains valid in the paraxial region but, which also contains all the leading terms of the previous radiation solution of [12]. It may be remarked that previous results which have been reported earlier by others, were based on a far less accurate asymptotic evaluation of such radiation integrals associated with a general convex surface, because of a simplifying assumption which is inherent in their work. Our present analysis reveals that such an asymptotic analysis must be done by a different approach which circumvents the inherent approximation present in the previously reported approaches to recover the leading terms which are valid outside the paraxial zone as in [12]. The theoretical solution to the problem of EM radiation in the paraxial zone by sources on a convex surface is presently complete and is now being tested for accuracy by comparison with other independent approaches. When the work on the radiation problem is completed, it will be extended subsequently to deal with the problem of EM scattering within the paraxial regions in almost the same manner as the radiation solution was obtained via an extension of the surface field (mutual coupling related) solution through the use of the appropriate surface currents in the radiation integral.

c. Slope diffraction

If the field incident at the edge of a wedge or the shadow boundary of a convex surface has a rapid spatial variation, a slope diffraction term must be added to the ordinary UTD. The slope diffraction term is proportional to the spatial derivatives of the incident field. It ensures that the spatial derivatives of the resulting radiation pattern are continuous at the shadow and reflection boundaries so that there are no "kinks" in the calculated pattern.

The derivation of slope diffraction terms for ordinary wedges formed by plane surfaces and for convex cylinders has been described in the two preceding annual reports, and a dissertation based on this work has been written [14]. The rough draft of a paper on this subject has been written and an effort is being made to extend the solution to a curved wedge formed by curved surfaces, where the present result may fail at the reflection boundary.

d. Diffraction by a discontinuity in surface curvature

The diffraction by an edge in a perfectly conducting surface formed by a discontinuity in surface curvature such as occurs in the cone sphere and the hemispherically capped cylinder, contributes strongly to the radiation in the vicinity of the reflection boundary where it compensates for the discontinuity in the reflected field. It may also contribute strongly to the axial backscatter from a body of revolution with a discontinuity in surface curvature. The geometry of the problem is depicted in Figure A-13.

A diffraction coefficient for the discontinuity in surface curvature has been described in the 1981 and 1982 annual reports. The solution is restricted to the case where the direction of incidence is normal to the edge. The purpose of the present work to obtain a simpler expression for this diffraction coefficient and to generalize it to the oblique incidence case.

It has been noted by Chu [15] that the curved wedge diffraction coefficient obtained by Kouyoumjian and Pathak [16] can be used to calculate the diffraction by a discontinuity in surface curvature in the vicinity of the reflection boundary. Although the first two terms in the curved wedge diffraction coefficient vanish in this case, the second

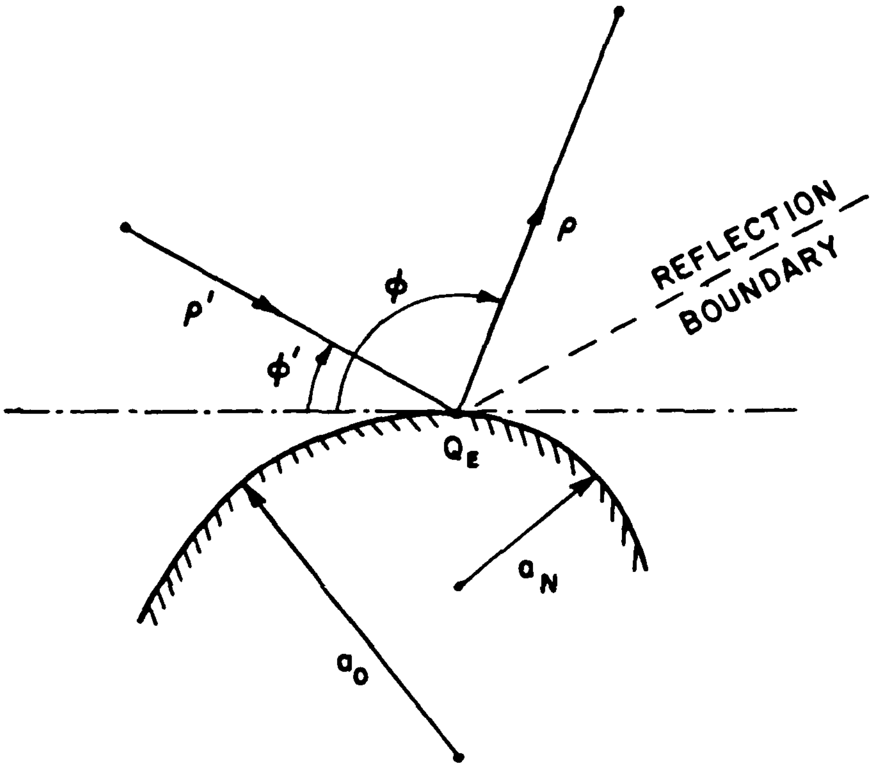

Figure A-13. Diffraction by a discontinuity in surface curvature.

pair of terms associated with the reflected field do not. They correctly compensate the discontinuity in the reflected field at the reflection boundary. However, outside the transition region of the reflection boundary, the diffracted field obtained by this method does not reduce to the correct, non-uniform asymptotic form given by Senior [17]. Starting with the expression for the curved wedge diffraction coefficient, a diffraction coefficient for the discontinuity in curvature was derived, which reduces to the solution given by Senior away from the reflection boundary and exactly compensates the discontinuity in the reflected field at the reflection boundary. It can be used at oblique incidence and is computationally simpler than the diffraction coefficient described in the 1982 annual report. Away from grazing incidence and diffraction, the two diffraction coefficients give virtually the same numerical results.

Since the new diffraction coefficient is based on the curved edge diffraction coefficient, it can not be used when the direction of incidence or diffraction grazes the surface unless the surface in question is planar. It is expected that this restriction can be removed by incorporating the generalized reflection coefficient given by Pathak [18] into the solution. Work on this extension is being carried out.

3. Diffraction of Non-Ray Optical Fields (Source Close to An Edge)

In the conventional form of the Uniform GTD, it is assumed that the incident field is a ray-optical field, which implies that it is polarized in a direction perpendicular to the incident ray. In general, this requires that the source of the incident field be sufficiently far from the point of diffraction so that the component of the incident field parallel to its ray path (the component in the radial direction from the source) is negligible at the diffraction point. However, in some applications this is not the case, e.g., a monopole antenna may be mounted at or very close to an edge on a ship or the edges of wings and stabilizers. This case is also of interest in the development of the Hybrid GTD/Moment Method solution, where it is desired to calculate the input impedance of a wire antenna close to an edge.

An asymptotic solution for the diffraction of the fields of electric and magnetic dipoles close to the edge of a wedge has been obtained. The basic approach is to determine the field close to the edge of the wedge; the far field of the dipole is then found using reciprocity. The asymptotic analysis of the diffracted field proceeds as done earlier [16] except that higher order terms are retained. The diffraction coefficient has the form of a 3x2 matrix which contains radial and cross-polarized components. This solution has been used to accurately calculate the fields of dipoles which are only a few tenths of a wavelength from the edge [19]. This result has been improved further and the components of the dyadic diffraction coefficient have been expressed more compactly. The analysis has recently been extended to the case of spherical wave illumination of the wedge. Both the source and field points may be close to the edge in the present solution, which also includes a slope diffraction contribution. This solution satisfies reciprocity and the continuity conditions at shadow and reflection boundaries. It is ready for numerical testing in the manner described in the following paragraph.

The dyadic Green's function described in section 2.b converges rapidly when the source point is close to the edge and so it is convenient to employ it to numerically check the solutions described in the preceding paragraph. It is hoped that the two types of solutions for edge diffraction can be combined so that we will have a more useful computational algorithm for edge diffraction. This is particularly important in the paraxial region where the high frequency solutions described in the last paragraph lose accuracy.

4. Caustic Field Analysis

The GTD is a very convenient and accurate procedure for analyzing high frequency radiation, scattering, and diffraction problems. However, the GTD suffers from a limitation inherent in ray methods; namely, it cannot be employed directly to evaluate fields at and near focal points or caustics of ray systems. The fields at caustics must, therefore, be found from separate considerations [20,21].

In certain problems such as in the diffraction by smooth, closed convex surfaces or by surfaces with a ring-type edge discontinuity, it is possible to employ the GTD indirectly to evaluate the fields in the caustic regions via the equivalent ring current method [22,23]. However, even the equivalent ring current method fails if the incident or reflection shadow boundaries are near or on a caustic.

The recently developed uniform GTD (or UTD) solution for the scattering and diffraction of waves by a convex surface [11,12,13] offers clues as to how it may be employed indirectly to obtain the far zone fields in caustic regions where the surface is illuminated by a distant source. In the latter case, the shadow boundary and caustic transition regions tend to overlap. The far zone fields in the near axial direction of a closed surface of revolution illuminated by an axially directed plane wave can be expressed in terms of an equivalent ring current contribution plus a dominant term which may be interpreted as an "effective aperture integral". The latter integral can be evaluated in closed form for surfaces of revolution with on-axis illumination. In the near zone, where the shadow boundary and caustic directions are sufficiently far apart, only the equivalent ring current contribution must remain significant. The generalization of that solution to treat non-axial incidence and also closed convex surfaces which are not necessarily surfaces of revolution forms the subject of future investigation.

Another related and interesting problem which is presently under study involves the analysis of high frequency electromagnetic diffraction by perfectly conducting planar surfaces (or plates) with a smooth convex boundary. In this problem, the planar face of the plate gives rise to caustic effects. For certain aspects, the caustic and specular reflection directions can coincide so that a direct use of UTD becomes invalid. The present study is aimed at determining a proper modification of the UTD so that a new and efficient equivalent current method can be used in these situations. Away from the caustic and confluence of caustic and specular directions, the modified UTD solution must reduce to the conventional GTD solution. More related problems involving a confluence of diffracted ray caustic and geometrical optical shadow boundary transition regions will be investigated in the future phases of this work.

5. Electromagnetic Dyadic Green's Function

Electromagnetic dyadic Green's functions are useful in that they allow one to calculate the fields of an arbitrary source distribution in a systematic fashion. In the case of special Green's dyadics which account for the source radiation in the presence of any boundaries, i.e., structures, they form the starting point for the asymptotic high frequency analysis of canonical problems in the uniform geometrical theory of diffraction (or UTD). In the latter application, it is implied that a Green's dyadic for the canonical geometry is known in the first step; this Greens' dyadic is then generally transformed into a useful form in terms of appropriate integrals if it is not originally available in that form (since it could originally be given as a series expansion), and finally, the intgrals are evaluated asymptotically to extract the high frequency UTD solution of interest.

A relatively simple method has been developed recently for constructing the complete eigenfunction expansion of time-harmonic electric ($\bar{E}$) and magnetic ($\bar{H}$) fields within exterior or interior regions containing an arbitrarily oriented electric current point source. In particular, since these fields $\bar{E}$ and $\bar{H}$ pertain to the case of point source excitation, they yield directly the complete eigenfunction expansion of the corresponding electric and magnetic dyadic Green's functions $\bar{\bar{G}}_e$ and $\bar{\bar{G}}_m$ that are associated with $\bar{E}$ and $\bar{H}$, respectively.

The expansion of $\bar{\bar{G}}_e$ and $\bar{\bar{G}}_m$ obtained here is expressed in terms of only the solenoidal type eigenfunctions which satisfy the required boundary and radiation conditions. In addition, the expansion of $\bar{\bar{G}}_e$ also contains an explicit dyadic delta function term which is required for making that expansion complete at the source point. This explicit dyadic delta function term in $\bar{\bar{G}}_e$ is obtained readily in the present approach from a simple condition that the eigenfunction expansion must satisfy at the source point, provided one interprets that condition in the sense of distribution theory.

A paper has been wtitten on the above topic, namely

"On the Eigenfunction Expansion of Electromagnetic Dyadic Green's Functions", by P.H. Pathak, IEEE Transactions on Antennas and Propagation, AfP-31, No. 6, pp. 837-846, November 1983.

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B. Hybrid Techniques

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A General Description of Hybrid Techniques

The method of moments (MM) provides a means of solving electromagnetic boundary value problems in terms of a set of simultaneous linear equations. In general, the electromagnetic boundary value problem is formulated as an integral equation for the unknown surface fields on the antenna or scatterer and the integral equation is then reduced to a system of equations by expanding the unknown in terms of a basis set and by enforcing this expansion to satisfy the boundary conditions in some average sense through the use of testing functions. However, the MM procedure can become inefficient and cumbersome if the number of unknowns (coefficients of the expansion or basis functions) becomes large as is the case for antennas or scatterers which are not small in terms of wavelength. On the other hand, the geometrical theory of diffraction (GTD) exploits the local nature of high frequency wave propagation, diffraction and radiation, thereby reducing the antenna radiation or scattering problem to calculating the fields associated with just a few rays emanating from edges, tips, and shadow boundaries (of smooth convex surfaces), and also from other discontinuities in the geometrical and electrical properties of the antenna or scatterer. Although the GTD is a high frequency technique, it works rather well, even for structures which are only moderately large in terms of the wavelength. However, the use of the GTD is limited by the number of available diffraction coefficients for characterizing a particular type of electrical and/or geometrical discontinuity. It is obvious that a procedure is desirable which would overcome the limitations of the individual MM and GTD approaches. Such a procedure, referred to as the "hybrid" GTD-MM procedure, can indeed overcome the limitations of the individual MM and GTD approaches by actually combining the best features of both methods. In particular, GTD provides the form of the local field over any part of the antenna or scattering structure, which is at least moderately large in terms of the wavelength; hence, the form of the GTD field could be viewed as a set of basis functions for the expansion of the unknowns in the MM formulation. The unknown coefficient associated with this type of GTD basis or expansion functions is then the diffraction coefficient for the surface field calculations if the unknown in the integral equation happens to be the surface field. Thus, by using the local GTD field form outside the region where the structure is small in terms of the wavelength, the number of unknowns is thereby vastly reduced in the MM procedure. The expansion for the unknown within regions (of the structure) which are small in terms of wavelength, is of course, done according to the conventional MM approach (perhaps using a subsectional basis set such as rectangular pulses, etc). Clearly, the hybrid GTD-MM procedure can solve problems far more efficiently than the MM procedure as the frequency increases. Also, it can provide a useful check on future diffraction coefficients as and when they become available.

While the hybrid GTD-MM procedure will in general be employed to essentially obtain numerical diffraction coefficients, other hybrid techniques which combine high frequency methods and numerical methods different from the MM procedure will also be studied. Thus, in a broader sense, the area of hybrid techniques will emphasize useful combinations of high frequency techniques with numerical methods for solving a variety of interesting and useful electromagnetic radiation and scattering problems.

At the present time, the following topics are under investigation in the area of hybrid techniques.

1. Problems of diffraction by perfectly-conducting structures involving special types of edges.

    a) Diffraction by a perfectly-conducting convex surface with a discontinuity in surface curvature.

The problem of the diffraction of EM waves by a perfectly-conducting surface with a discontinuity in surface curvature, which is illuminated by an external source, was analyzed using the hybrid techniques. In addition, a heuristic uniform diffraction coefficient associated with a curvature discontinuity was developed as mentioned in a previous annual report. While work on the latter problem has been completed at the present time, a paper describing this work is being prepared and it will be submitted for publication in the near future. A second related problem involving the radiation by a source on a plane surface which is joined smoothly to a curved surface was also analyzed by the hybrid method and the results were applied to the design of a horn antenna with rounded edges. That work which was published in two papers was likewise described in a previous annual report. Furthermore, an efficient analytical solution was also recently developed for the latter problem; a paper indicating the development of this analytical solution is being prepared and it will be submitted for publication in the near future.

b) Diffraction by a Perfectly-Conducting Half Cylinder

As a continuation of the work described in part a) above, the problem of the diffraction of EM waves by a perfectly-conducting half cylinder was analyzed during the past year. The geometry of the half cylinder is shown in Figure B-1; it represents one of the simplest examples of a finite sized structure with an edge in an otherwise smooth convex boundary. An analysis of the EM scattering by this two-dimensional geometry is useful for understanding the coupling between edge and surface diffraction mechanisms, and it is also useful in the analysis of the RCS of convex bodies with edges. It is noted that a fully general UTD ray solution for such a configuration is not available at this time. In the present work, a hybrid GTD-MM technique has been employed to analyze the scattering by this half-cylinder configuration. Both, the TE and TM polarizations have been treated. This hybrid solution is very efficient since, in general, only 8-12 unknowns are required to represent the induced surface current in the moment method procedure which employs the mixed (hybrid) basis representation for the current in terms of a few pulse basis functions around the edges, and the uniform GTD type basis functions for the current elsewhere on the surface of the half cylinder. It is noted that the above number of unknowns stays the same in this hybrid GTD-MM approach even if the electrical size of the cylinder is increased; in contrast, the conventional MM approach always requires an increase in the number of unknowns with an increase in the cylinder size. Some typical results for the TE and TM radiation patterns of an electric current line source in the presence of the half cylinder of Figure B-1 that are based on the hybrid GTD-MM procedure are illustrated in Figures B-2 and B-3 which also show a comparison with the corresponding conventional MM solutions for the case in Figure B-2 for a cylinder whose perimeter is approximately 10λ (here λ=wavelength). In figure B-2, the number of unknowns (using a pulse basis set) in the conventional MM solution is 100; whereas, in the present hybrid GTD-MM solution, the number of unknowns in only 12. In the case of Figure B-3, no MM solution is indicated as it becomes very inefficient for such a large sized cylinder. A paper describing this work will be submitted for publication in the near future.

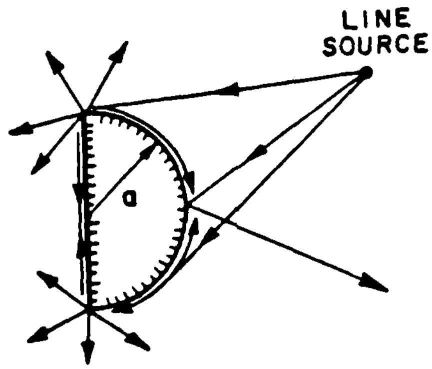

Figure B-1. Diffraction by a half cylinder of radius = a.

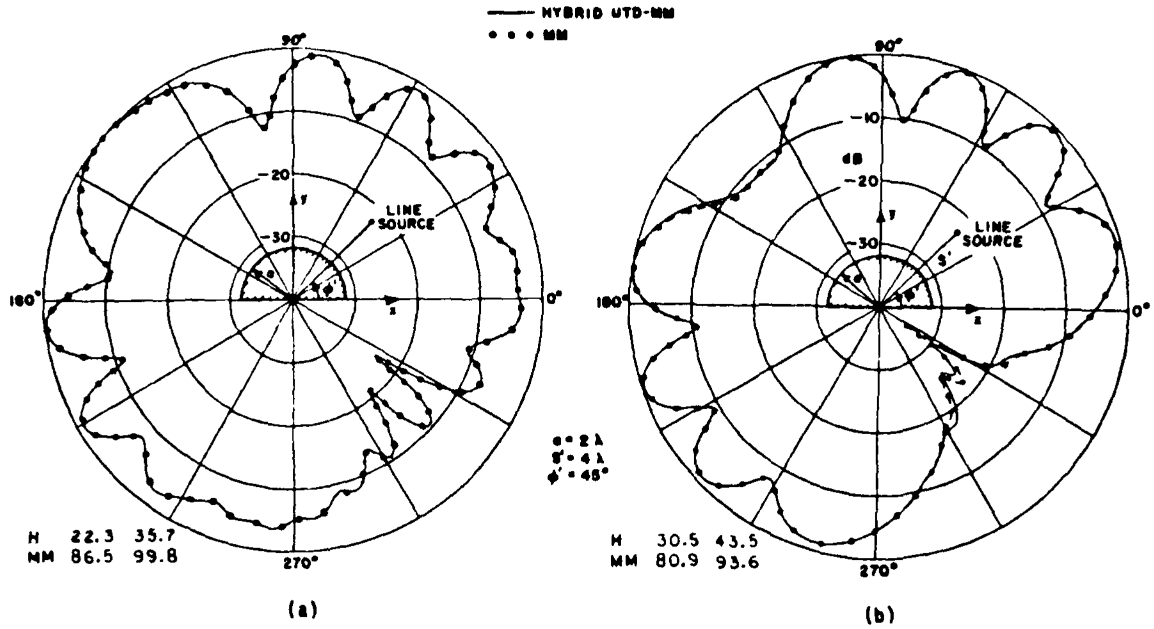

Figure B-2. Far-field pattern of a magnetic (a) and an electric (b) line source in the presence of a semi-circular cylinder of radius 2λ.

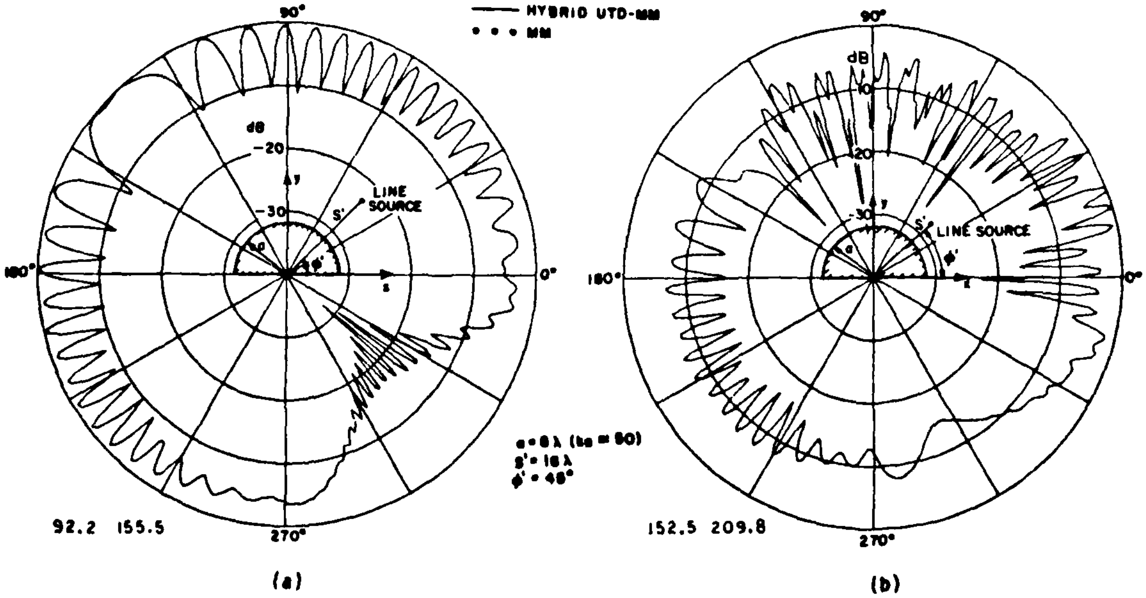

Figure B-3. Far-field pattern of a magnetic (a) and an electric (b) line source in the presence of a semi-circular cylinder of ka = 50.

It is also noted that the above work was recently published as an M.S. thesis:

S. Srikanth, "Hybrid UTD-MM Analysis of the scattering by a Perfectly Conducting Semi-Circular Cylinder", A thesis, presented in partial fufillment of the requirements for the Degree Master of Science in Electrical Engineering at the Ohio State University, 1984.

2. Problems of Diffraction by Edges formed at junctions between perfectly-conducting and dielectric boundaries.

Currently, work is in progress to obtain an efficient, hybrid GTD-MM solution to the problem of TM_0 surface wave diffraction by the structure shown in Figure B-4(a). This work is of interest in the design of radomes for a conformal slot antenna array. The dielectric is made inhomogeneous near the junction of the dielectric conducting body in order to reduce the surface wave reflection from that junction. A computer program searches for the selection of dielectric material to accomplish this purpose. Some results of the surface wave reflection coefficient and the radiation pattern for the case where the dielectric is homogeneous are shown in Figures B-5 and B-6. Also shown in these figures are solutions of the same problem obtained by Pathak [1] using a Wiener-Hopf type technique. The agreement between the two methods is generally very good. One should note that the technique employed by Pathak in [1] cannot be extended to treat the problem where the dielectric is inhomogeneous. The computer program is being modified to study the inhomogeneous dielectric problem is using the hybrid GTD-MM technique. Both surface wave and plane wave incidences pertaining to

TE and TM polarizations are considered when the boundary beneath the dielectric is either an electric conductor or a magnetic conductor. Combinations of these general solutions enable one to solve the problem posed in Figure B-4(b). These solutions will be reported and published in the future.

3. Problems associated with coupling by apertures.

A hybrid GTD-MM solution to the problem of an exterior line source excitation of an aperture in a parallel plate wave guide as seen in Figure B-7 was initiated during this past year. It is of interest to know the energy scattered from and penetrated through the aperture. A proper choice of special Green's functions in the integral equation formulation of this problem requires one to find only the unknown electric field in the aperture. The aperture field can be obtained using the moment method technique for small apertures and the hybrid technique for large apertures. An example of the aperture field is shown in Figure B-8 which was obtained using the conventional moment method technique; this solution will be used for comparison when the hybrid solution is completed. Extension to the case of a very large aperture using the hybrid technique will be evaluated in the future. The fields scattered by the aperture into the interior and exterior regions can be found easily once the aperture field is determined. An analysis of two related problems involving the EM diffraction by an aperture in a thick perfectly conducting screen, and by a groove in a planar conducting surface, respectively, which employed a combination of

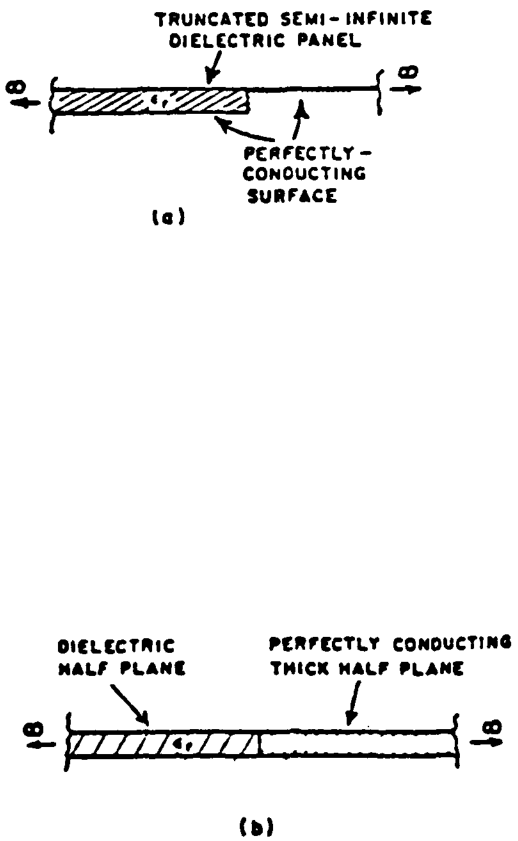

Figure B-4. Discontinuity formed by the junction of a dielectric and perfectly-conducting structure.

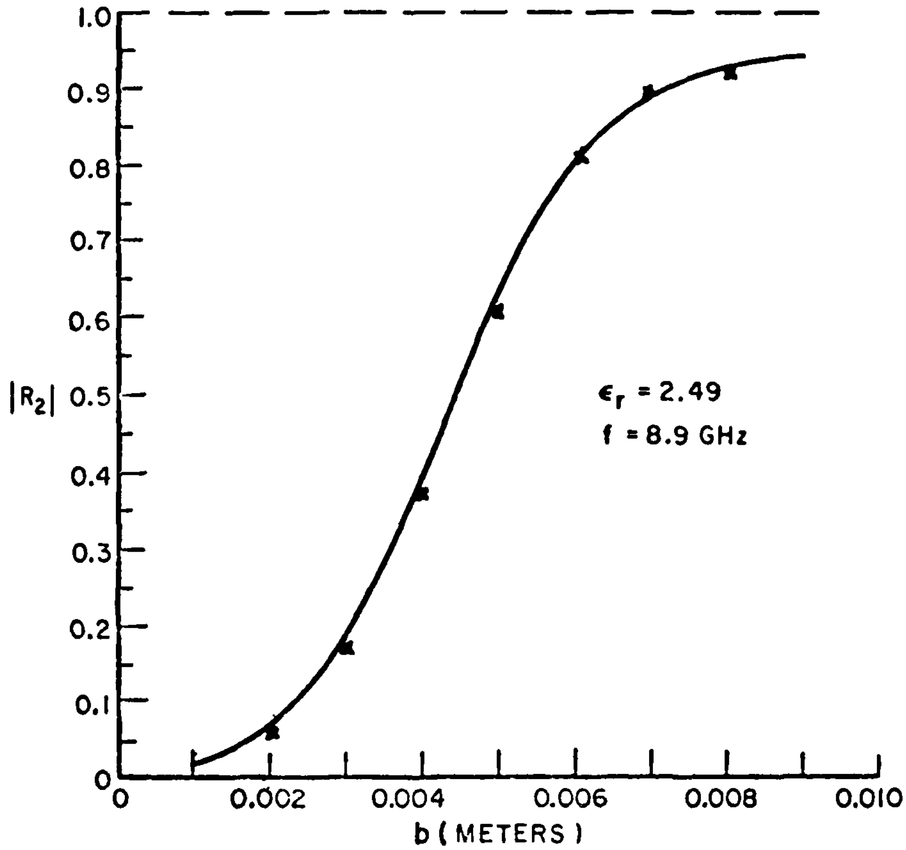

Figure B-5. Surface wave reflection coefficient as a function of the dielectric thickness. Solid curve is reproduced from reference [1].

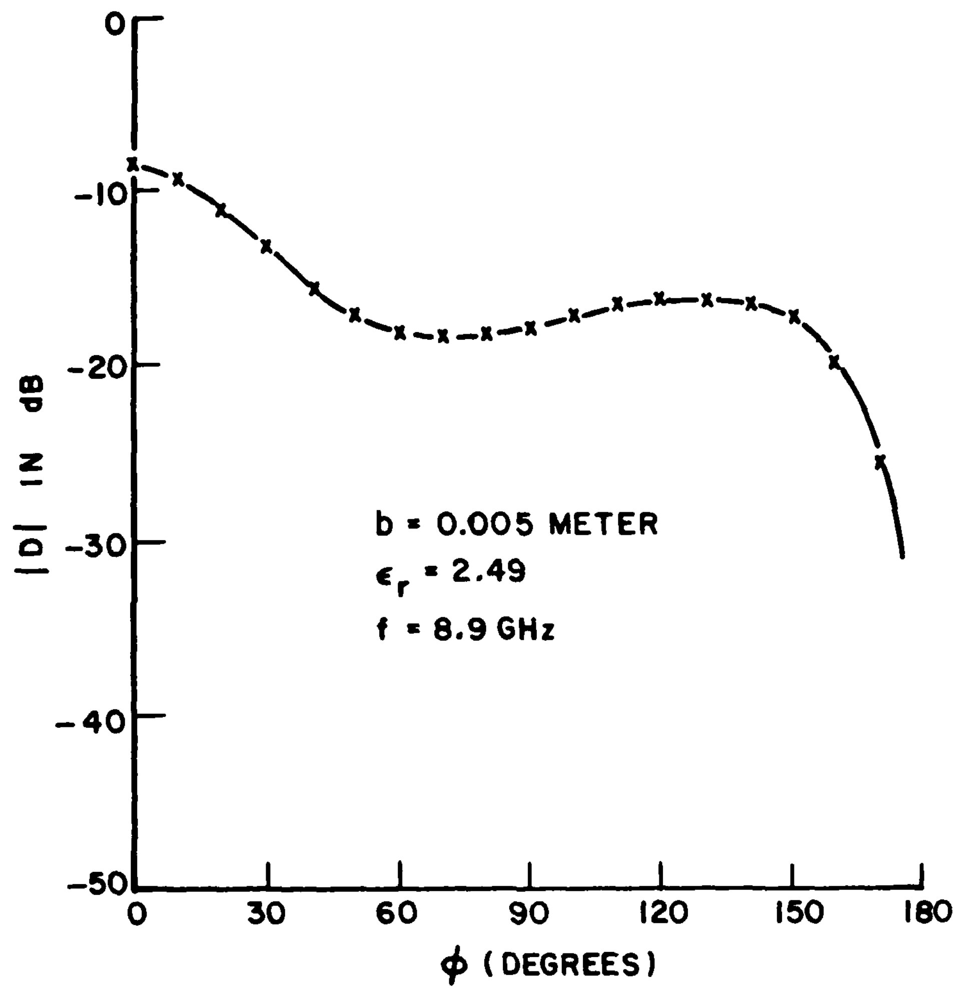

Figure B-6. Radiation pattern of the structure in Figure B-1(a) with surface wave incidence. Solid curve is reproduced from reference [1].

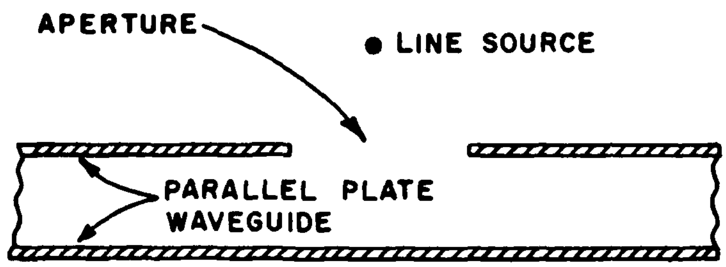

Figure B-7. Exterior line source excitation of a parallel plate waveguide through an aperture in the wall.

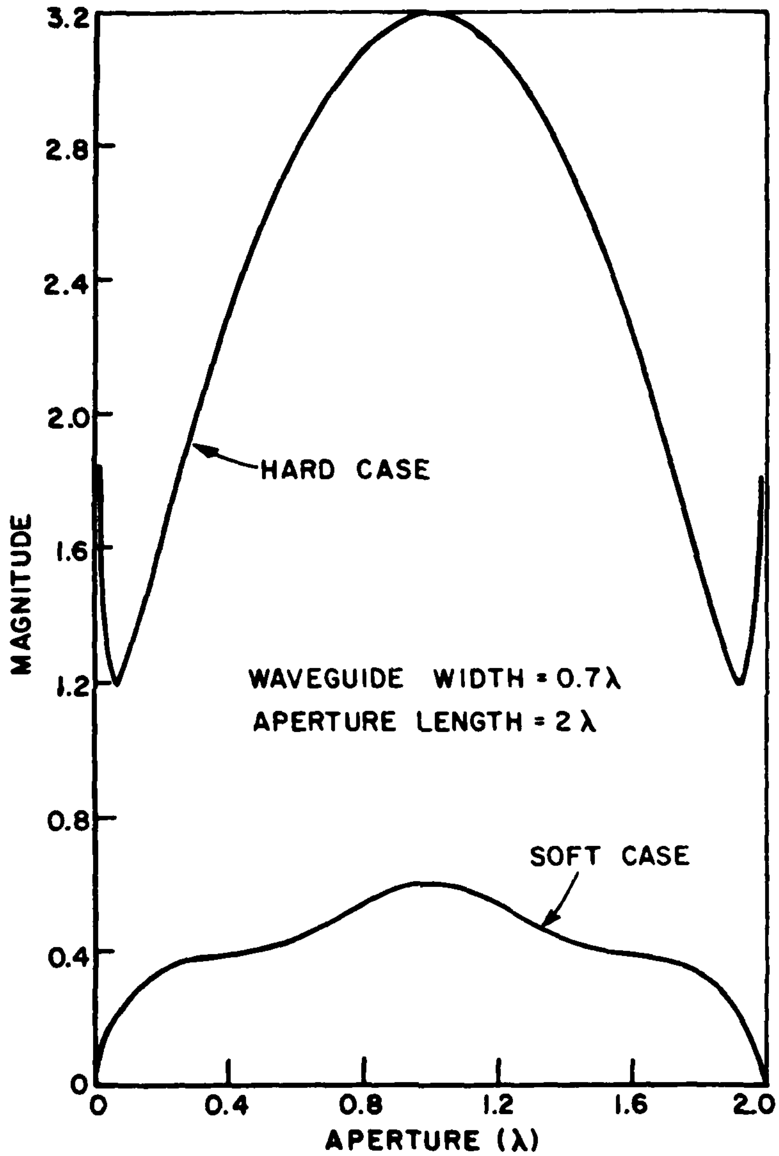

Figure B-8. Relative magnitude of the electric field across the aperture. The line source is at a distance 1λ above the center of the aperture.

moment method and multiple scattering techniques, was mentioned in the last annual report [2]. A technical report and a paper dealing with these two related problems is currently in preparation; namely, "EM Scattering by Slits and Grooves in Thick Perfectly-Conducting Planar Surfaces", by R. Kautz, P.H. Pathak, and L. Peters, Jr.

4. Analysis of Microstrip Antennas.

Microstrip antennas are light-weight, relatively low-cost antennas which can be employed conformally on many practical structures including aircraft and missile shapes. It is therefore of interest to efficiently analyze the radiation from a single microstrip antenna element and also from an array of electrically small microstrip patch antennas which are placed conformally on an electrically large perfectly-conducting smooth convex surface. The latter problem, as depicted in Figure B-9, can be handled efficiently if one combines low frequency techniques (for handling the electrically small microstrip patches) with the high frequency ray technique (for handling the electrically large convex surface). Presently, work has been initiated to analyze the asymptotic high frequency surface fields of an electric current source (such as that associated with a microstrip patch) on a "thin" grounded dielectric planar surface. This solution would provide the dominant contribution to the asymptotic high frequency estimate of the Sommerfeld integral type surface Green's function which would be useful for calculating the unknown current distribution only on the microstrip patch or on the

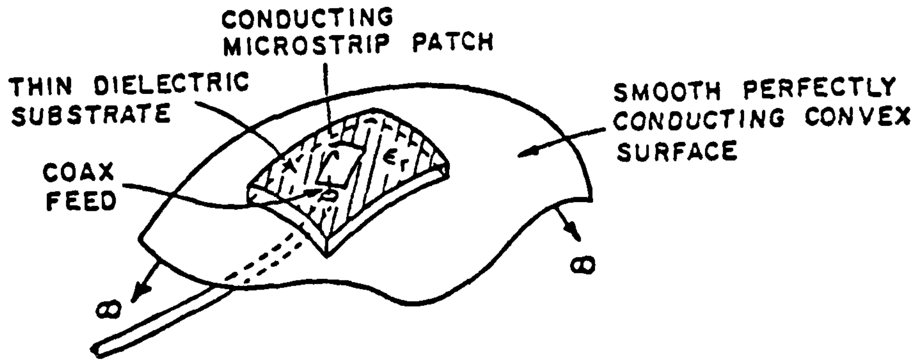

Figure B-9. Microstrip antenna element on a convex surface.

array of microstrip patches. The remaining asymptotic contribution from the edges of the dielectric substrate will be accounted for separately using the results described in sections A-1(b) and A-1(c) dealing with the diffraction by a discontinuity in surface impedance and by the edge of thin dielectric half plane on a perfectly-conducting surface. The object here is to find a simple and accurate asymptotic approximation for the aforementioned surface Green's function which remains uniformly valid in the neighborhood of the source so that the MM calculation can be made efficient. It is noted that a direct calculation of the Sommerfeld integral type representation of the surface Green's function makes the MM procedure inefficient especially for an array of microstrip antennas. Presently, such a simple approximation for the surface Green's function has been obtained for a two dimensional planar and convexly curved perfectly conducting surface with an extremely thin dielectric coating (which may thus be approximated by an impedance boundary condition). It is therefore felt that a similar approach could be employed in the three-dimensional situation as is being presently investigated. This approach would automatically account for the mutual coupling between various microstrip patches (or elements) in an array environment. The case of a moderately thick dielectric substrate on a planar as well as on a convexly curved perfectly conducting surface will be dealt with in the future phases of this study once the present approach is found to be sufficiently accurate and efficient on the thin dielectric planar substrate for the three-dimensional problem.

5. Reflector Antenna Synthesis

Large, offset array fed parabolic reflector antennas are being considered for use in multiple beam type antenna applications. It would hence be of interest to investigate approaches for developing an efficient solution for the synthesis of such a multiple beam type reflector antenna configuration, by combining high frequency techniques and appropriate numerical techniques. The object of the present study has been to essentially determine a feed distribution in the "vicinity of the focal region which generates the desired multiple beams. In addition it is desirable that information on the size of reflector and feed region which would tend to optimize the design should be contained in this approach. Recently, work has been initiated to study this problem from the reciprocal point of view in which the field within the focal region due to a plane wave incident on the reflector is investigated; here the direction of the incoming plane wave corresponds to that of any of the multiple beam directions of interest via the reciprocity theorem for EM fields. The focal region fields are being investigated using an approximate procedure which it is hoped would not only be accurate but also be very efficient as compared to the conventional approaches based on a direct numerical evaluation of the physical optics approximation to the radiation integral for calculating these fields. Efficiency is of importance in synthesis problems. The solution to this reciprocal problem will be properly combined in the future phases of this study to deal with the general multiple beam synthesis problem mentioned above if the present approach is found to be successful in it's initial phases.

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C. Integral Equation Studies

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B.W. Kwan, Graduate Research Associate

Introduction

This section will describe the recent progress in integral equation studies. Briefly, we are developing a solution to the problem of a half-plane edge coated by a dielectric material. The basic technique is a method of moments (MM) solution of the exact integral equation. The motivation for studying this problem, a brief outline of the theory, and some early results are given below.

In order to understand the motivation for considering the dielectric coated half-plane edge, it is helpful to review our past work under JSEP sponsorship. The long range goal of this work has been to do the basic researach which will permit the modeling of complex geometries in the resonance region (i.e., at frequencies where the body is not electrically large). To this end, we have developed techniques, termed surface patch or plate modeling, for general perfectly conducting structures. In plate modeling, one models a general structure as an interconnection of polygonal plates. In particular we have worked on the following basic problems under JSEP sponsorship:

1. MM solution for a rectangular plate [1-3]
2. MM solution for the junction of a thin wire and a rectangular plate [1,2,4-6]

3. MM solution for a polygonal plate [7,8]

4. MM solution for the junction of two or more polygonal plates [8]

5. MM solution for a material (i.e., dielectric) plate [9]

6. MM solution for the junction of a material and a perfectly conducting plate.

Note that problems 1-4 refer to perfectly conducting plates. Problems 1-5 represent our past work, and we are currently working on 6.

The results of problems 1-4 have been applied (under non-JSEP sponsorship) to the modeling of perfectly conducting complex shaped bodies. This has resulted in general purpose user oriented computer codes [10,11], which have been ordered and distributed to over 40 members of industry, government, and universities. For example, Figure C-1 shows a three view plot of 14 polygonal plates interconnected to form a plate model of the Concord aircraft [8]. At the frequency of interest, the Concord is about 2 wavelengths in length. Figures C-2 and C-3 show a comparison of the computed and measured magnitude and phase of the RCS in the azimuth plane and for horizontal polarization. Clearly, one can visualize how the polygonal plates can be interconnected to form a model of ships, satellites, buildings, etc. Also, wires can be used to model antennas on the structures.

Thus, we have made substantial progress in the modeling of generally shaped structures, provided that they are essentially perfectly conducting. However, now consider the problem of modeling a general shape, like the Concord, if all or part of it were constructed

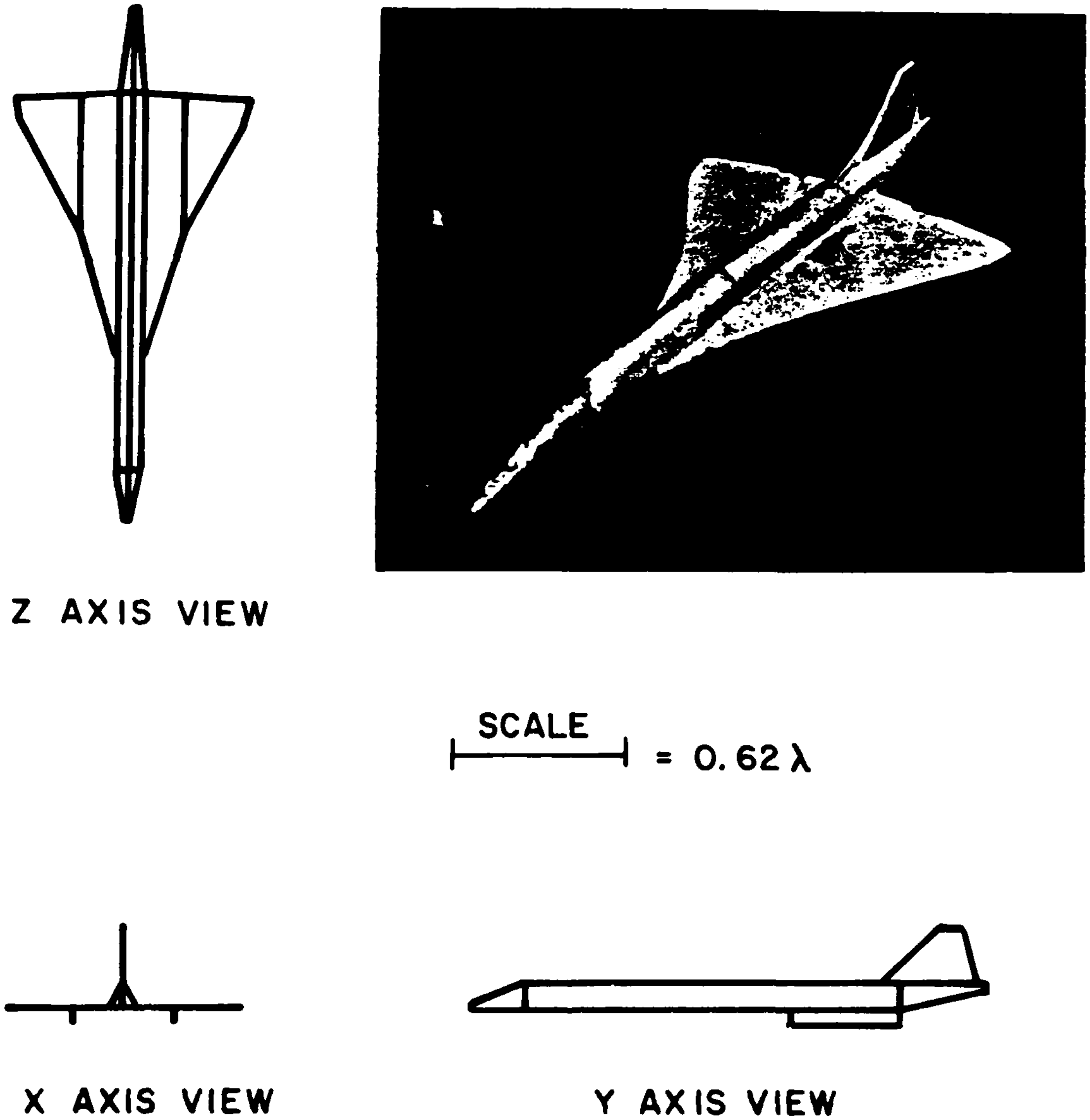


Figure C-1. A 14 polygonal plate model of the Concord aircraft.

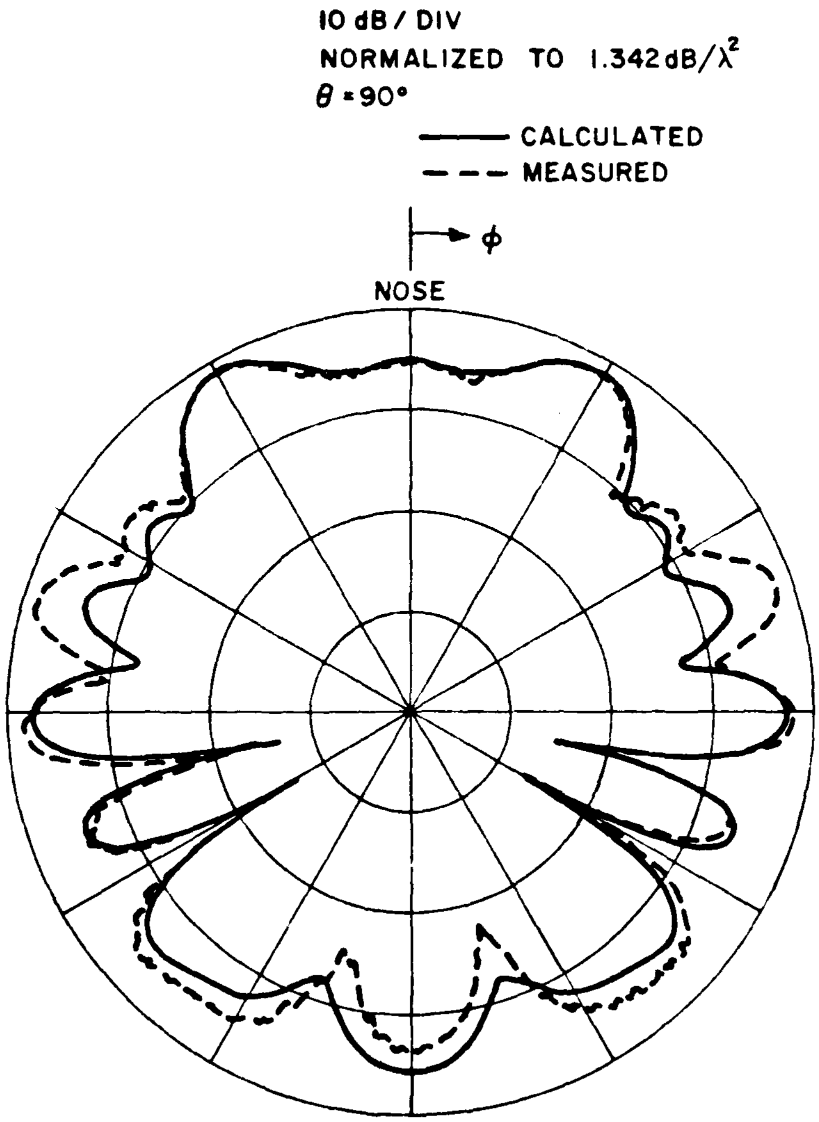


Figure C-2. The magnitude of the RCS of the Concord in the azimuth plane and for horizontal polarization.

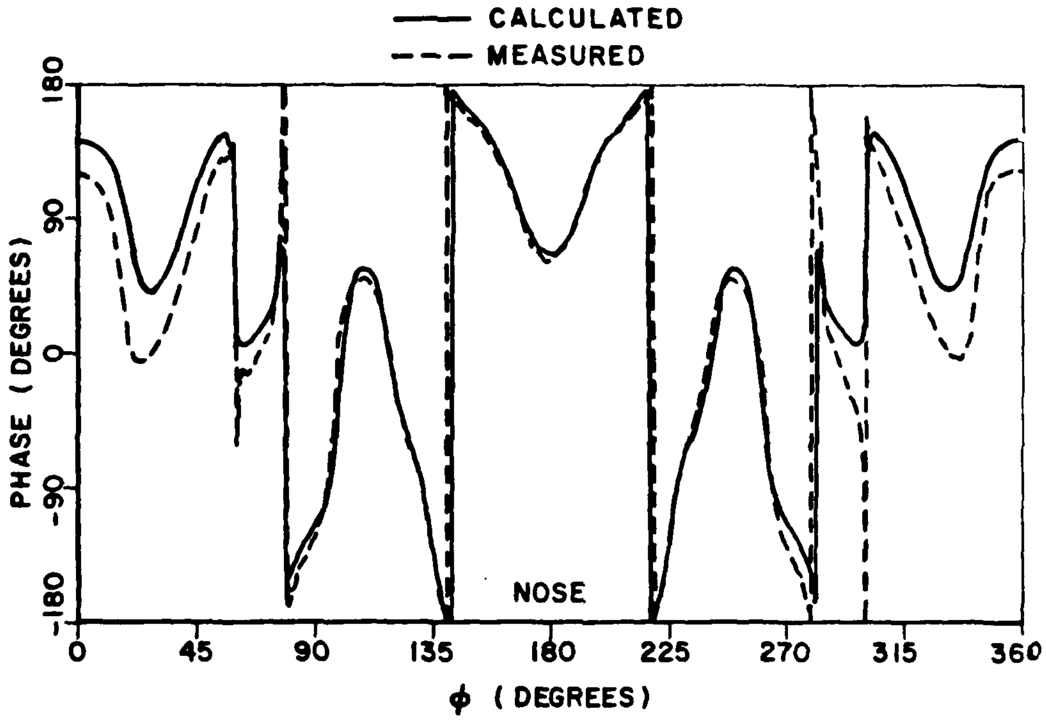


Figure C-3. The phase of the backscattered signal of the Concord in the azimuth plane and for horizontal polarization.

from some nonperfectly conducting material. This is a problem of practical interest, since portions of aircraft are being made from the so-called composite materials, which may be penetrable materials. Also, non-metallic materials are often used to modify the radar-cross-section (RCS) of aircraft. As an example, consider the Concord with composite wings. This geometry could be analyzed if the capability to model material plates, and the interconnection of material and perfectly conducting plates, were added to existing techniques for the modeling of interconnections of perfectly conducting plates. Recently we have developed an MM solution for a material plate [9] (i.e., 5 above). Our current work centers on the problem of the junction of a perfectly conducting and a material plate. Initially, this is being done by solving the equivalent 2-D problem of the junction of a dielectric slab and a half-plane. By studying this 2-D junction, it is hoped that information will be obtained to permit the solution of the 3-D material plate/perfectly conducting plate junction.

Brief Theory

This section will briefly outline the theoretical solution for a half-plane edge coated with a dielectric slab. Figure C-4a shows the currents ($\underline{J}_i$, $\underline{M}_i$) radiating in the presence of a half-plane edge coated with a dielectric slab. The dielectric may be inhomogeneous, with permittivity, ϵ. We will use the following notation for the fields of ($\underline{J}_i$, $\underline{M}_i$):

$(\underline{E}_i, \underline{H}_i)$ = fields in the presence of the uncoated half-plane

$(\underline{E},\underline{H})$ = fields in the presence of the coated half-plane

In Figure C-4b the volume equivalence theorem is used to replace the dielectric with free space and the equivalent electric volume polarization currents.

$$\underline{J} = jw(\varepsilon-\varepsilon_0)\underline{E} \tag{C-1}$$

In Figure C-4b, the fields $(\underline{E},\underline{H})$ are generated by $(\underline{J}_i, \underline{M}_i)$ and $\underline{J}$ radiating in the presence of the uncoated half-plane. If we denote $(\underline{E}_J,\underline{H}_J)$ as the fields of $\underline{J}$ in the presence of the half-plane, then Equation C-1 requires

$$\underline{E} = \underline{J}/jw(\varepsilon-\varepsilon_0) = \underline{E}_i + \underline{E}_J. \tag{C-2}$$

Equation C-2 is essentially an integral equation (written in symbolic form) for the unknown current, $\underline{J}$. Equation C-2 has been solved by the numerical technique, known as the MM, which transforms it into a system of simultaneous linear equations. The details of the MM solution will not be presented here.

Some initial numerical results of the MM solution of Equation C-2 will now be presented. The geometry for this slab is shown in Figure 5. Here we have a dielectric with a relative permittivity of 4. The slab has dimensions 2 by 0.05 wavelengths, and is located symmetrically with respect to the half-plane edge. Thus, the half-plane is at $x > 0$ and $y = 0$, while the dielectric slab is in the volume $-1.0 < x < 1.0$ and

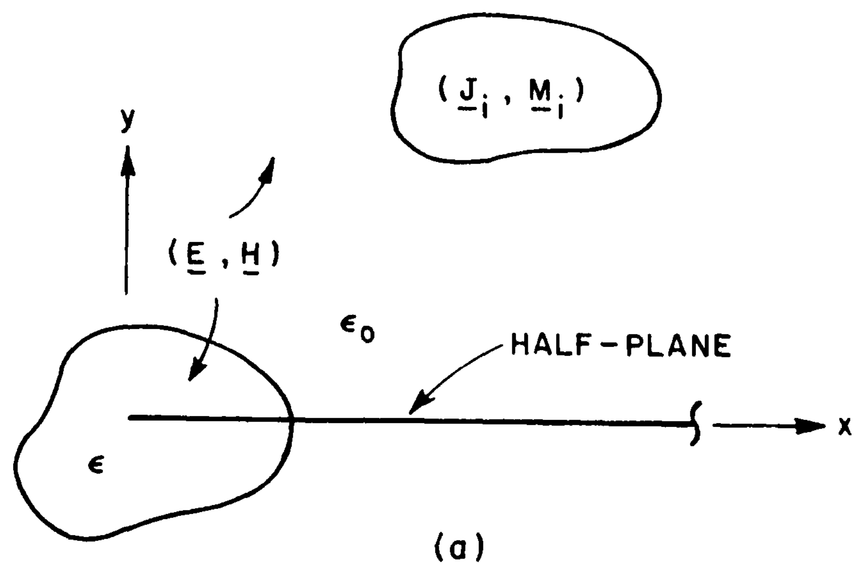


Figure C-4a. The impressed currents radiating in the presence of a dielectric coated half-plane edge.

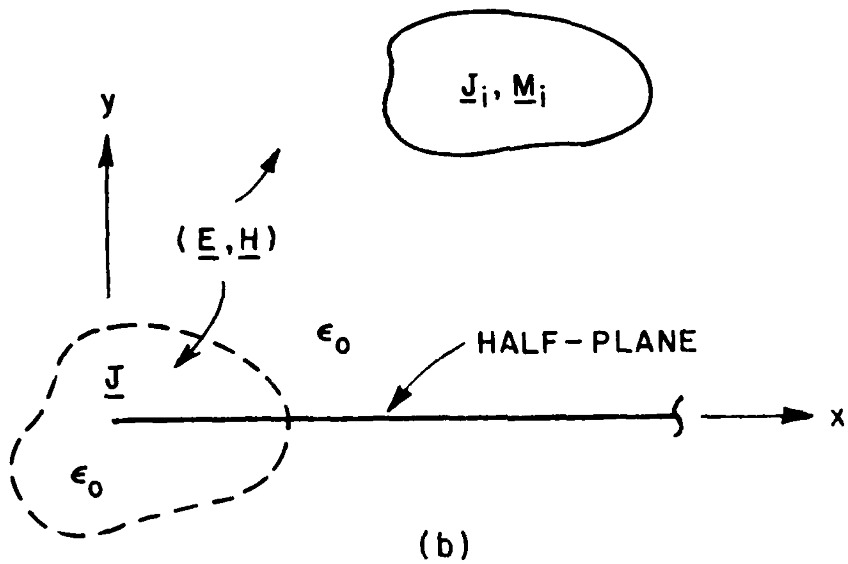
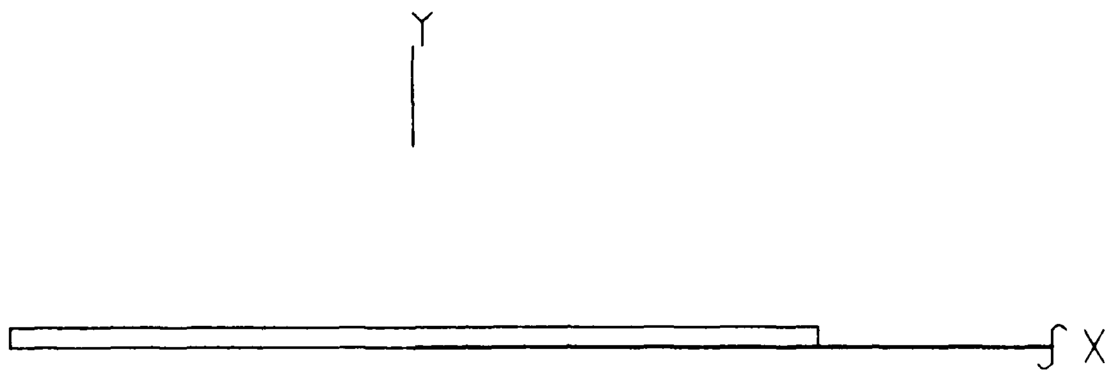


Figure C-4b. The dielectric is replaced by free-space and the equivalent volume polarization currents, $\underline{J}$.



DIELECTRIC BLOCK GEOMETRY (METERS) NO. MODES = 20

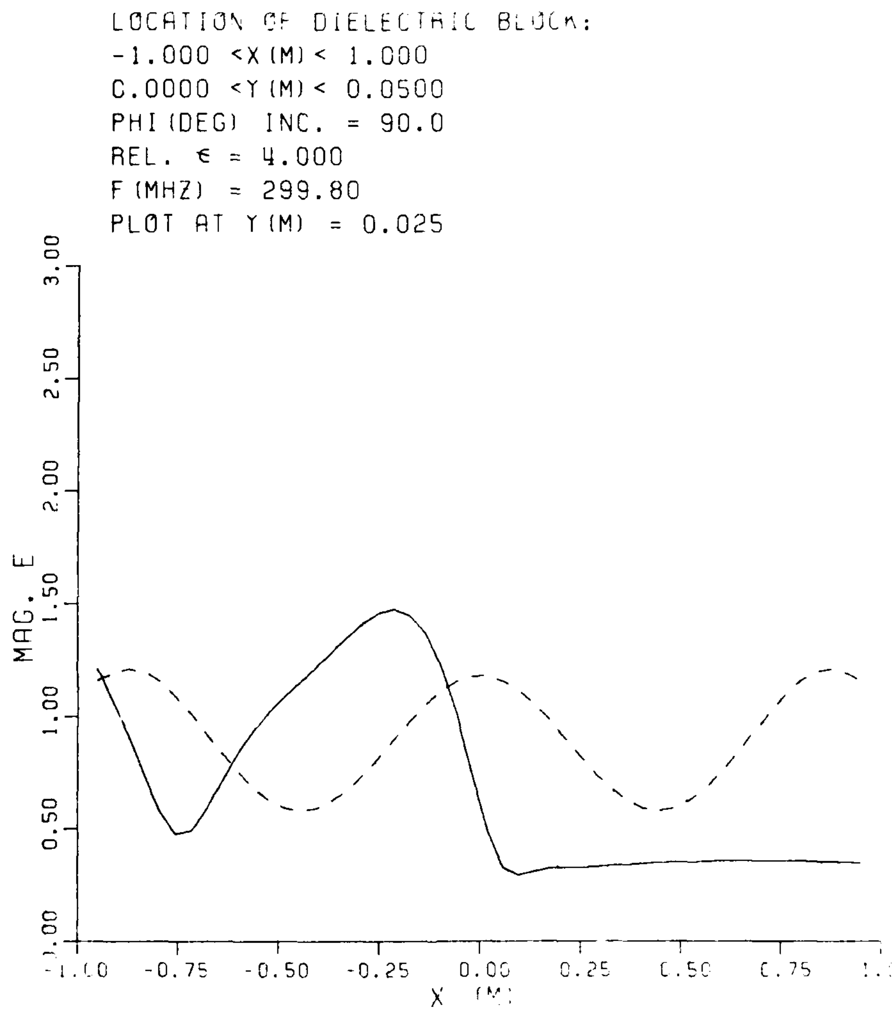
NB	XB1	XB2	YB1	YB2	YB3	YB4	REL E
1	-1.000	1.000	0.000	0.000	0.050	0.050	4.00

Figure C-5. Geometry for a dielectric coated half-plane.

$0.0 < y < 0.05$ wavelengths. The excitation is by a z polarized plane wave incident from phi = 90 degrees, which is broadside to the slab.

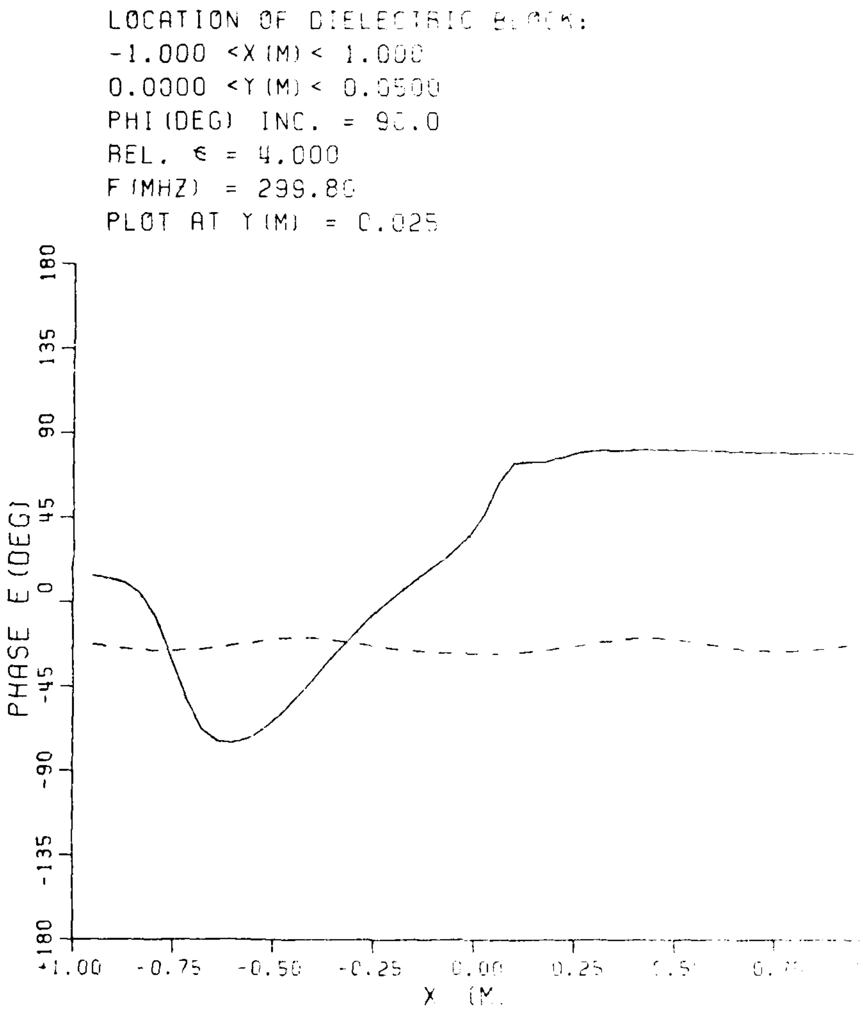
The solid line in Figures C-6a,b shows the magnitude and phase of the total z polarized electric field intensity in the center of the dielectric slab at $y = 0.025$ wavelengths. The dashed line in Figures C-6a,b shows the field if the half-plane were removed. Note that in the region $x > 0$, the field point is 0.025 wavelengths above the perfectly conducting ground plane. Thus, as expected, Figure C-6a shows that the magnitude of the tangential electric field is small. The solid line in Figures C-7a,b is the magnitude and phase of the ratio of $-E_z/H_x$ along a line 0.002 wavelengths above the slab, and for $-3.0 < x < 2.0$ wavelengths. This ratio is essentially the surface impedance. The dashed line in Figure C-7 is a simple approximation to the surface impedance, based upon a transmission line model. Note that the magnitude and phase of the surface impedance computed via the MM tends to oscillate about the value predicted from simple transmission line theory. This oscillation is a result of energy diffracted from the half-plane edge.

The ability to generate data similar to Figure C-7 is one motivation for considering the dielectric slab/half-plane junction problem. In our previous solution for the material plate, we used a surface impedance approximation, based upon simple transmission line theory, to simplify the solution [9]. While the surface impedance approximation worked reasonably well for the isolated material plate, we



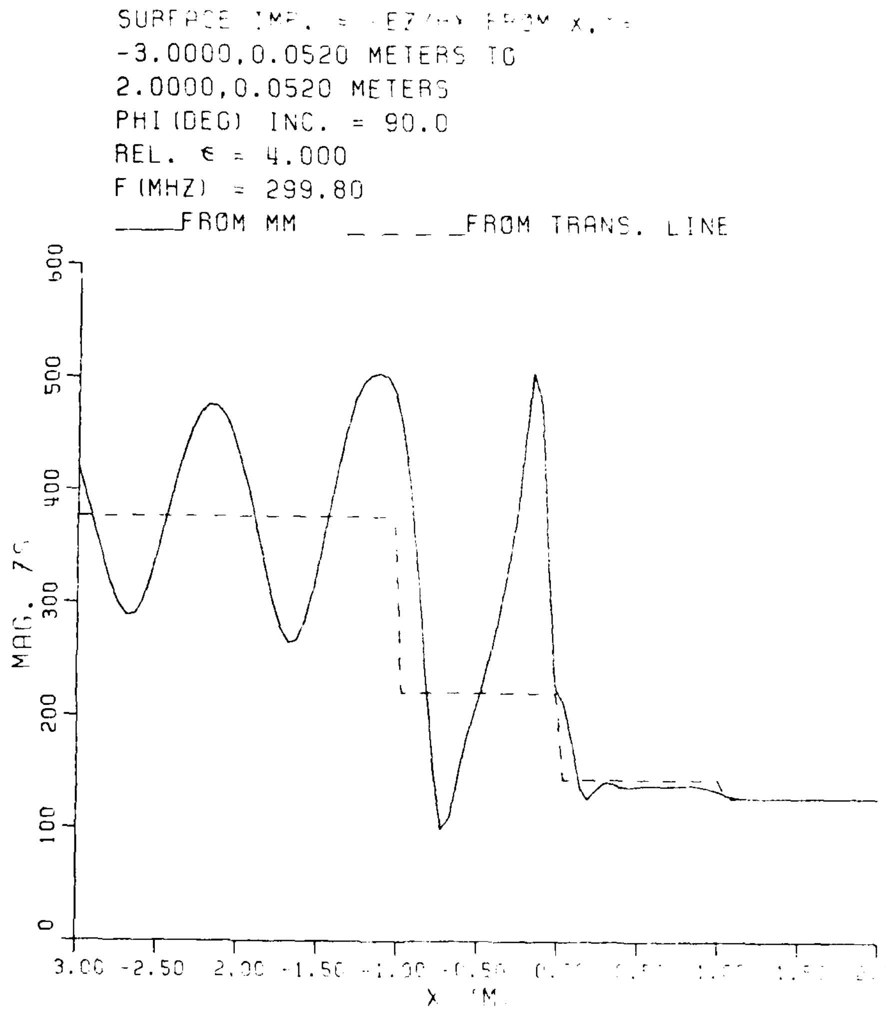
(a)

Figure C-6. The (a) magnitude and (b) phase of the total electric field in the dielectric slab, of Figure 5, and along its center line y = 0.025λ. The solid and dashed curves are with and without the half-plane, respectively.



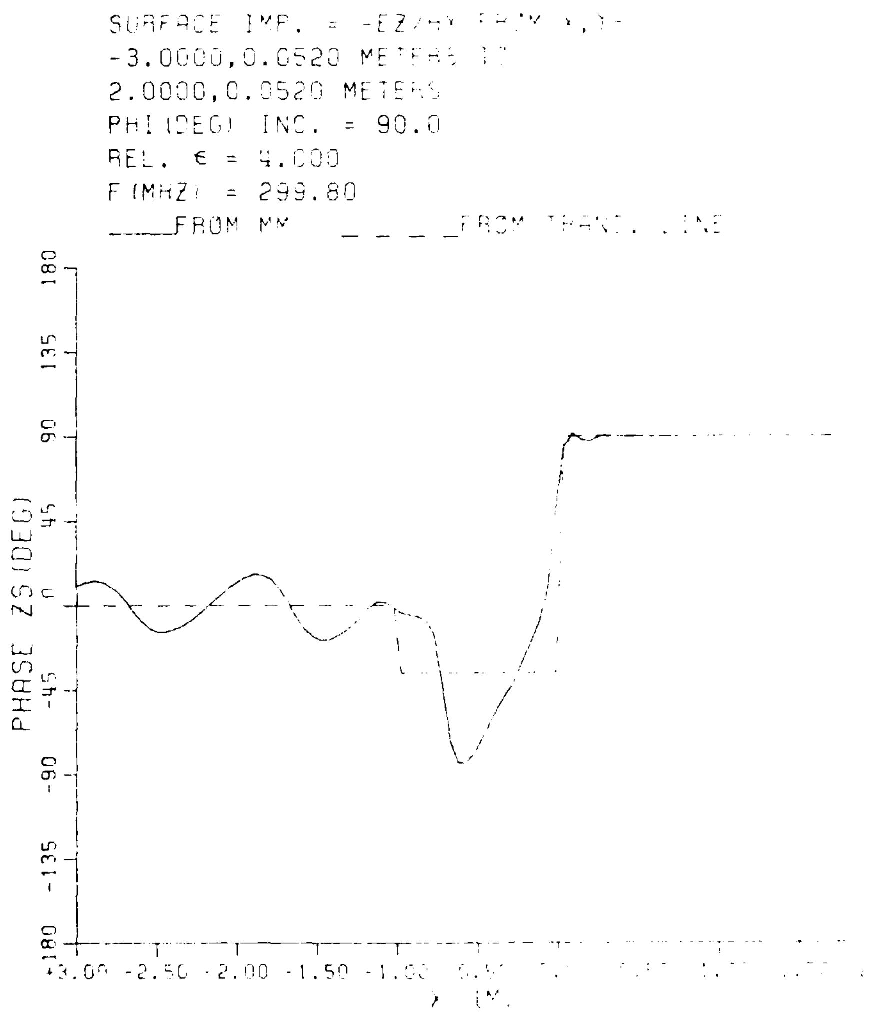
(b)

Figure C-6. (continued)



(a)

Figure C-7. The (a) magnitude and (b) phase of the surface impedance along the line y = 0.052λ. The solid and dashed lines are computed by the MM solution and by a simple transmission line model, respectively.



(b)

Figure C-7. (continued)

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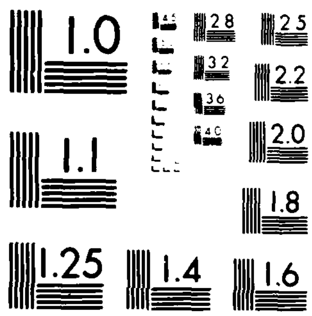

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

now wish to see to what extent it can be extended to the junction of a material and a perfectly conducting plate. Figure C-7 suggests, that at the junction of a material and a perfectly conducting plate, the simple transmission line model for computing the surface impedance may be usable, at least in an average sense.

Another problem, separate from the surface patch modeling techniques described above, was also studied under JSEP support. Briefly, in October 1983 we completed an Army Research Office (ARO) grant to study microstrip antennas. At the conclusion of this grant we realized that very significant results could be obtained, related to conformal microstrip arrays, if we were able to devote several additional months to this effort. This study of conformal microstrip arrays is being done under JSEP support.

The work being done can be briefly described as follows. At the conclusion of the ARO grant we had developed a rigorous eigenfunction solution for the self or mutual coupling between microstrip patches on a dielectric coated cylinder. Under JSEP support, we have obtained asymptotic approximations to the eigenfunction solution, based upon large cylinder radius. This work will lead to a Ph.D. dissertation [19] plus journal publications.

Recent JSEP Publications on this Task

This section will summarize the recent publications under JSEP sponsorship. The material plate solution has resulted in one journal paper [3], one paper scheduled for publication [9], one oral paper [12], and one Ph.D. dissertation [13]. The work on polygonal plate modeling has resulted in one paper scheduled for publication [8], one oral paper [14], and one masters thesis [15]. The work on plate modeling has been applied to the microstrip antenna, under partial JSEP sponsorship, and has resulted in one paper [16], one paper submitted for publication [17], and one oral paper [18]. A dissertation entitled "Mutual Impedance Computation for Conformal Microstrip Antennas" by B. Kwan will be completed this summer. It is expected that several additional papers will be generated by this work.

Summary

Recent effort has centered on the problem of a half-plane edge coated with a dielectric slab. A preliminary solution to this problem has been obtained. It is hoped that information gained from this problem will be useful in our larger goal of developing techniques for analyzing structures of general shape and composed of perfectly conducting as well as dielectric materials. In particular, it is hoped that it will be of use in modeling the junction of a perfectly conducting and a material plate using a surface impedance approximation. A second important output of the solution is to see how a dielectric coating on a half-plane edge may modify the diffraction from the edge.

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D. Scattering by Penetrable Geometries

Researchers: J.H. Richmond, Professor (Phone: (614) 422-7601)
W.J. Kent, Graduate Student

1. Introduction

The increased use of penetrable materials on aerospace vehicles leads to requirements for more efficient analytic treatment of such configurations. We may list the following examples of penetrable geometries: the dielectric radome, ablation coatings, composite media, and ferrite absorbers.

Although Richmond [1,2] published the first moment-method solutions for scattering by dielectric cylinders with arbitrary cross-sectional shape in 1965, the technique has not yet been extended to ferrite cylinders. A dielectric cylinder is modeled with electric polarization currents, while a ferrite cylinder requires magnetic (as well as electric) polarization currents.

In 1973, Richmond [3] developed a user-oriented moment method for scattering by a perfectly conducting polygon cylinder. Later, Wang [4] extended the theory and computer program to include a thin dielectric coating on the polygon cylinder. While promising, Wang's results might be improved by including surface waves in the analysis.

In the area of RCS control, Professor Leon Peters has suggested that a thin ferrite coating may offer unique properties that cannot be duplicated with a thin lossy dielectric coating. This idea has been reinforced by the numerical results of Hill [5] for the propagation constant of a surface wave on a thin lossy ferrite coating.

To take advantage of these unique properties, we require an analysis of scattering by a thin lossy ferrite slab, or a conducting strip with a thin ferrite coating. An analysis for the lossless case has been developed recently by Burnside and Burgener [6] with the GTD format. Their results agree closely with moment method calculations except for those situations where surface wave effects are dominant. The surface waves are not included in their analysis.

As discussed in an earlier section, Pathak and Rojas-Teran have applied the *Wiener-Hopf technique* to the thin dielectric half-plane. They have obtained excellent results, with some difficulty in the vicinity of grazing incidence.

In the next three sections we consider some examples of thin dielectric bodies and conducting surfaces with a thin dielectric coating. These examples are: a thin dielectric strip, a conducting circular cylinder partially coated with a thin dielectric layer, and finally a long straight wire with a thin dielectric coating.

2. Diffraction by a Thin Dielectric Strip

Richmond [7] has developed an efficient moment-method solution (with only three equations and three unknowns) for plane-wave scattering by a thin lossy dielectric strip (see Figure D-1) with the incident electric field vector parallel with the edges of the strip as in Figure D-2. The electric field intensity in the dielectric region was expressed in "physical basis functions" as the sum of three traveling waves:

$$E_z(x,y) = C_1 e^{f_1 x} \cosh(g_1 y) + C_2 e^{fx} \cosh(gy) + C_3 e^{-fx} \cosh(gy) \quad . \tag{D-1}$$

The first term represents the "forced wave", or the field induced in an *infinitely-wide* dielectric slab. The last two terms represent surface waves traveling in opposite directions across the thin dielectric strip. Galerkin's method is employed to determine the constants C_1, C_2 and C_3. Finally, the far-zone scattered field is calculated by considering the polarization currents radiating in free space. Figure D-3 illustrates the electric field distribution induced in a thin dielectric strip by a plane wave with grazing incidence. The results obtained with the new method (physical bases) show excellent agreement with those from the old method (pulse bases) which involved a system of 200 simultaneous linear equations.

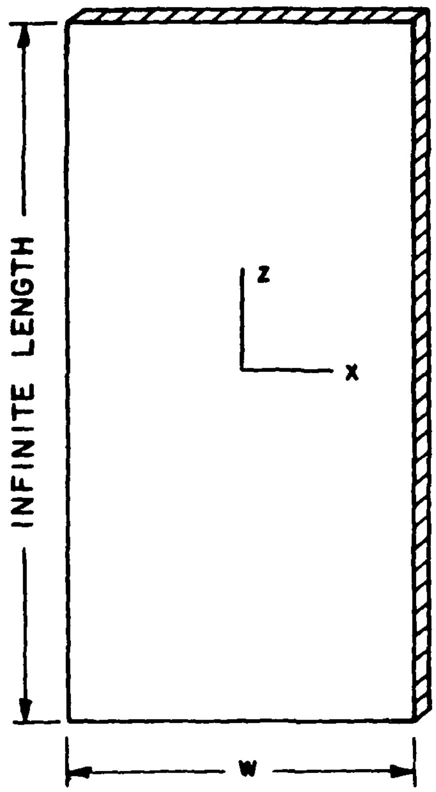

Figure D-1. A dielectric strip and the coordinate system.

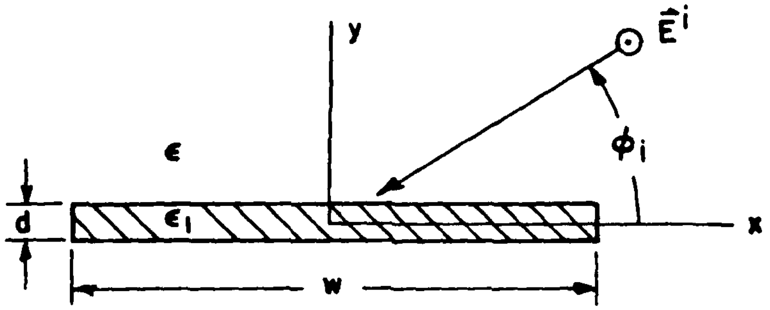

Figure D-2. Cross-sectional view of thin dielectric strip with incident plane wave.

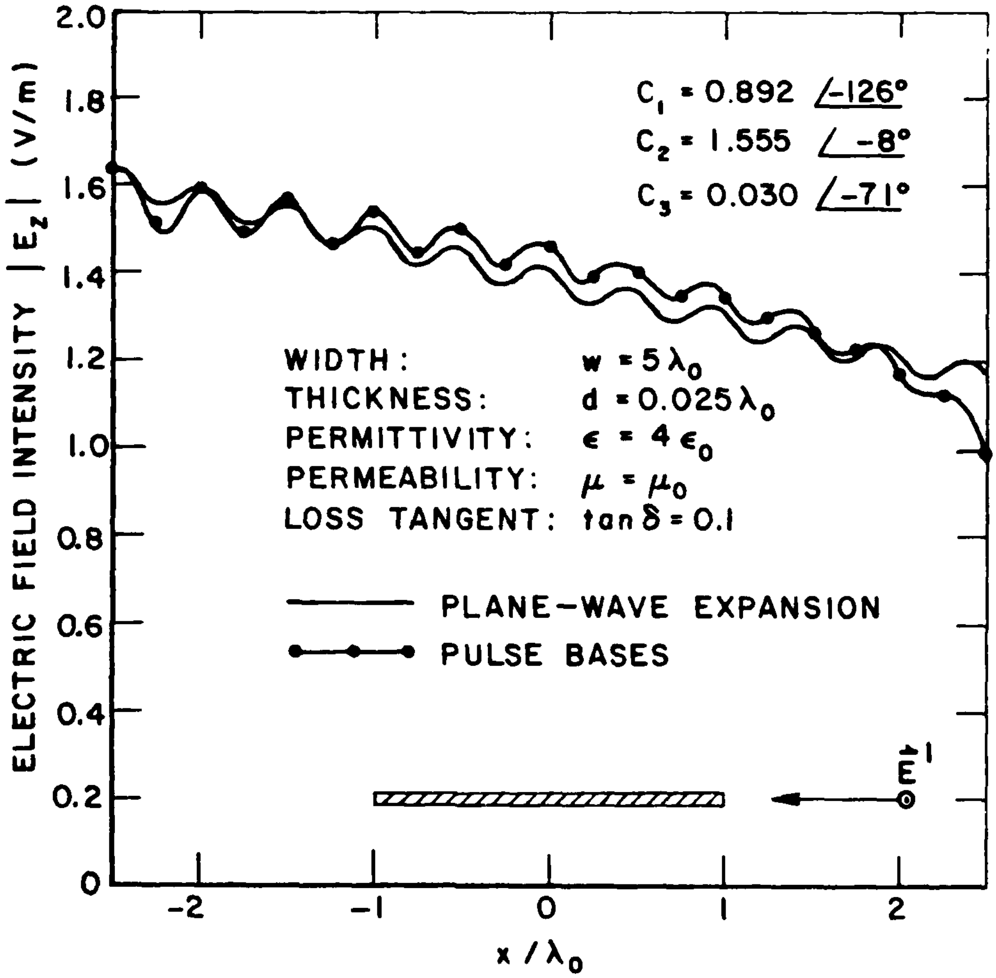

Figure D-3. Electric field distribution induced in thin dielectric strip by plane wave with grazing incidence.

In the current reporting period, Kent has applied the physical basis technique to the thin dielectric strip with the other polarization. Numerical results are not yet available.

3. Diffraction by Dielectric-coated Conducting Surfaces.

Figure D-4 illustrates an axial slot antenna radiating through a flush-mounted dielectric window in a conducting cylinder. In 1975, Richmond [8] applied the moment method to solve this problem. Although this represents an antenna transmitting problem, the same techniques can be applied in the scattering situation.

In the exterior free-space region, the field was expressed as a summation of cylindrical waves with integer order. In the dielectric region, the field was expressed as a summation of cylindrical waves with non-integer orders as determined by the angular extent of the region. The expansion coefficients in each region represent an infinite series of unknown constants. We expanded the field in the outer aperture (at radius b) in a Fourier series with N terms, and applied Galerkin's method to generate a system of N simultaneous linear equations for the N unknown Fourier coefficients.

Having solved in this manner for the aperture field distribution, we then readily determined the coefficients in the expansion for the field in the exterior region. This solution proved to be accurate and efficient, requiring only 20 simultaneous linear equations for a cylinder with a diameter of 38 wavelengths. In Figures D-5 and D-6, one may note excellent agreement between our calculations and the far-field

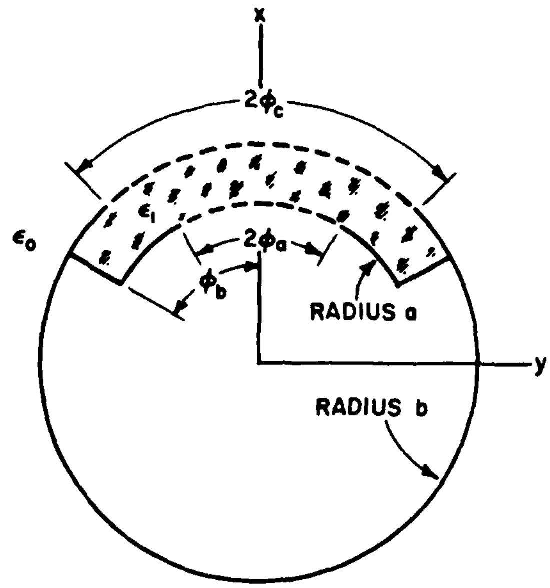

Figure D-4. An axial-slot antenna radiates through a flush-mounted dielectric window in a conducting circular cylinder.

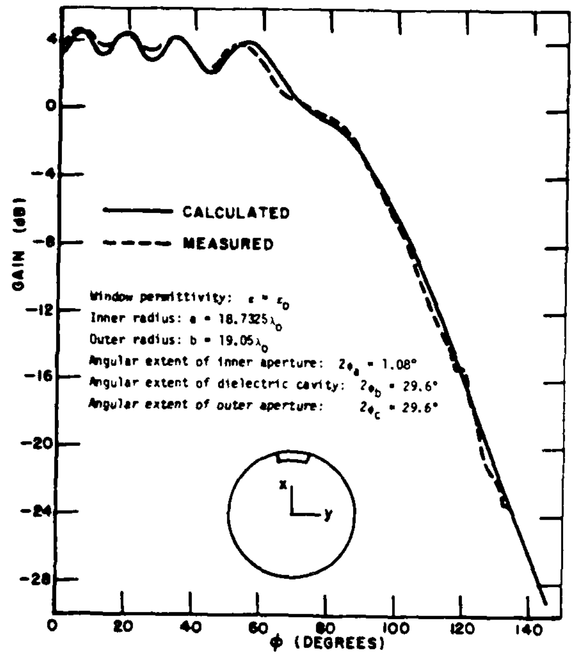

Figure D-5. Far-field pattern with $\varepsilon_r = 1$ in the slot.

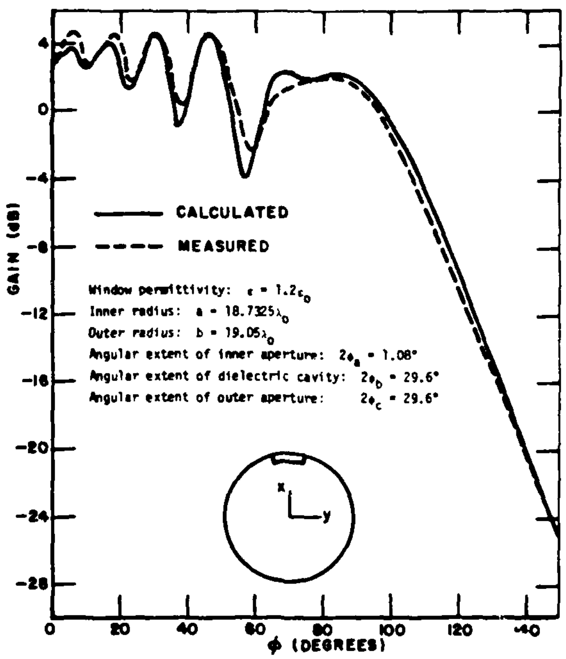

Figure D-6. Far-field pattern with $\varepsilon_r = 1.2$ in the slot.

patterns measured by Gilreath at NASA Langley. We are proposing to incorporate the "physical basis" concept into this eigenfunction technique, and to apply it to several interesting scattering geometries as illustrated in Figure D-7.

4. Dielectric Coated Wires

In 1976 Richmond and Newman [9] published the sinusoidal-Galerkin moment method for dielectric coated wires, and showed that the calculations give excellent agreement with measurements for dielectric-coated straight wires and square loops.

In the period from September 1983 to June 1984, Kent attacked the problem of a long straight wire with a thin dielectric coating and a plane wave incident. First he employed the sinusoidal-Galerkin moment method and found that it is slow when applied to very long wires. In order to develop a more efficient solution and to gain physical insight into the scattering process, Kent then expanded the current distribution on the long coated wire in "physical basis functions" as the sum of three terms: a forced wave and two surface waves traveling in opposite directions along the wire. He then applied Galerkin's method to determine the amplitudes of the three traveling waves. Finally, the far-zone scattered field was calculated readily from a knowledge of the current distribution.

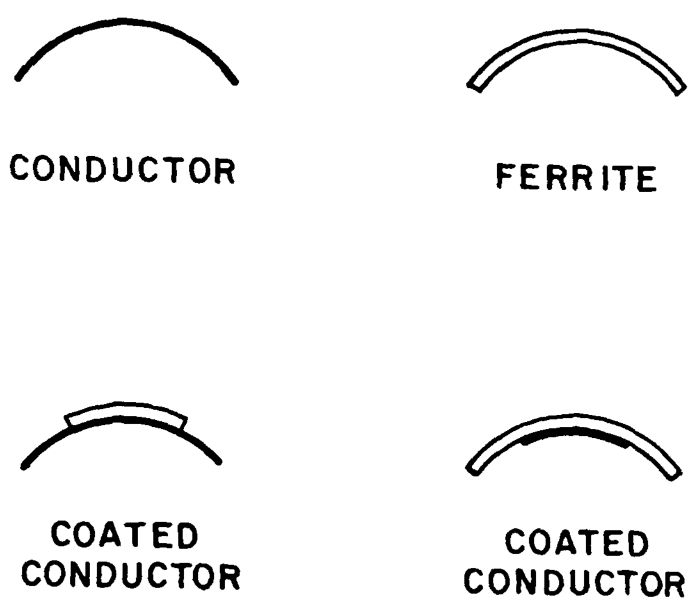

Figure D-7. Circular-cylindrical targets with the following compositions: conductor, ferrite, and conductor with thin ferrite coating.

Figure D-8 illustrates a wire with radius "a" and length ℓ. The outer radius of the dielectric coating is b. The angle of incidence is θ_i, and the scattering angle is θ_s. Figure D-9 illustrates the bistatic scattering patterns of a wire ($\ell = 7.958\lambda$) with a lossless dielectric coating and broadside incidence. Figure D-10 illustrates the bistatic scattering patterns of a wire ($\ell = 16.67\lambda$) with a lossy dielectric coating and oblique incidence. It may be noted in these examples that the new method (physical bases) shows excellent agreement with the old method (piecewise sinusoidal).

5. Accomplishments

In this section we shall outline our accomplishments through May 31, 1984.

In this period, Kent [10] completed about 90% of the research work for his Ph.D. dissertation.

Our new "physical basis" moment method was applied with excellent results to plane-wave scattering by a long straight wire with a thin dielectric coating.

The physical-basis concept was applied to a thin dielectric strip with the "other polarization" where the incident magnetic field vector is parallel with the infinitely-long edges of the strip. The theoretical development and computer programming have been completed, and debugging is in progress.

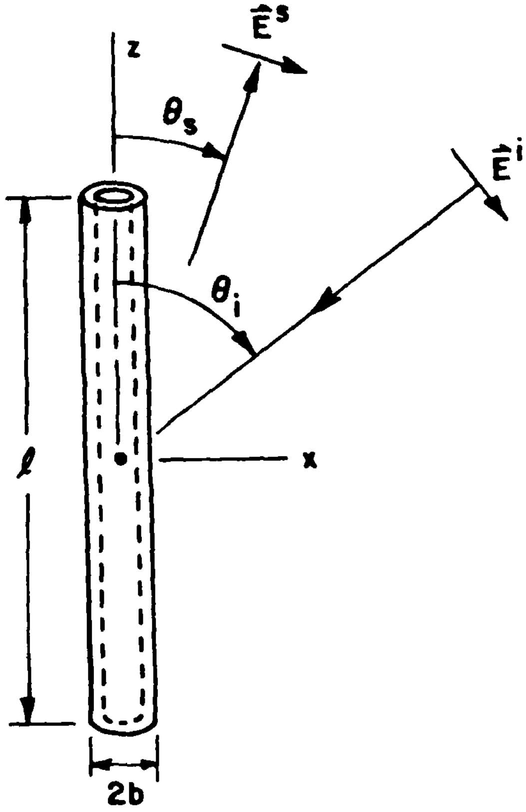

Figure D-8. A plane wave has oblique incidence on a straight wire with a thin dielectric coating.

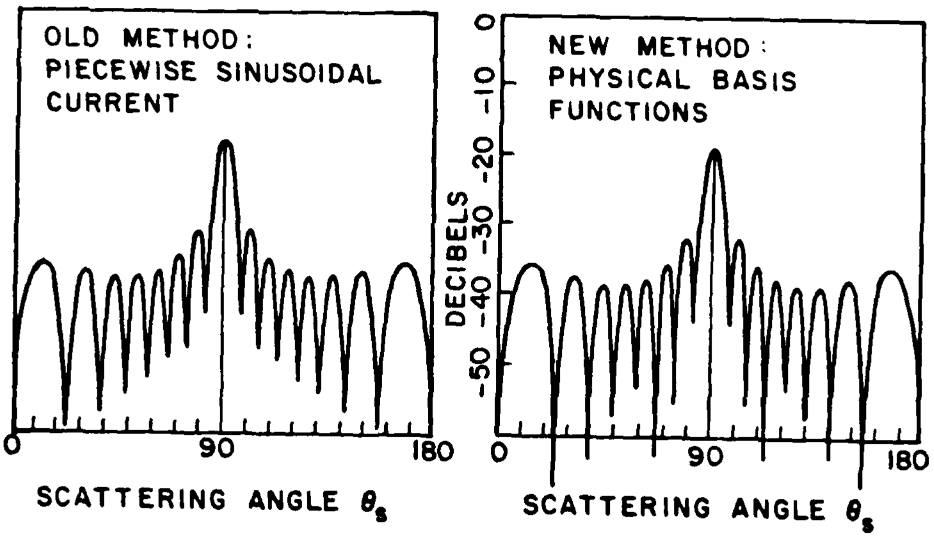

Figure D-9. Bistatic scattering patterns of wire with lossless dielectric coating and broadside incidence. (ℓ = 0.25 m, a = 0.2 mm, b = 0.3 mm, ϵ_r = 4, f = 9.55 GHz)

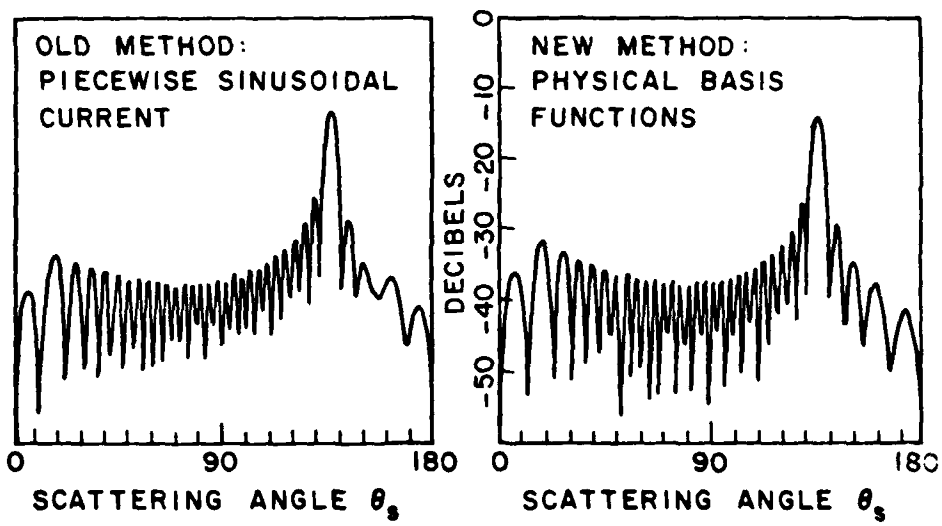

Figure D-10. Bistatic scattering patterns of wire with lossy dielectric coating and oblique incidence. (ℓ = 0.5 m, a = 0.2 mm, b = 0.3 mm, ϵ_r = 4, $\tan\delta$ = 0.1, f = 10 GHz, θ_i = 45°)

In the remaining portion of this contract period (June 1 to September 30, 1984), efforts will be focussed on scattering by a conducting circular cylinder partially coated with a thin ferrite layer.

6. Future Research

We propose to investigate scattering by thin curved ferrite strips with the aid of our new "physical basis" moment method. Having already demonstrated the technique with flat dielectric strips and coated wires, we propose to extend it to the following situations as illustrated in Figure D-7:

a. curved conducting strip

b. thin curved ferrite strip

c. curved conducting strip with thin ferrite coating.

In this study we will employ the cylindrical mode functions as described in section 3.

In each phase of this investigation, the results calculated by the new method will be tested against experimental measurements or independent calculations. Since measurements or independent data are not available in most cases, alternative formulations and programs will be developed for test purposes.

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E. Time Domain Studies

Researchers: D.L. Moffatt, Associate Professor (Phone: (614) 422-5749)

Dr. J.D. Young, Associate Director

Dr. Nan Wang, Senior Research Associate

Chun-Yue Lai, Graduate Research Associate

Hyo Tae Kim, Graduate Research Associate

William Leeper, Graduate Research Associate

Introduction

The optimum exploitation of the interaction of electromagnetic waves and material objects can only be achieved with a clear understanding of how the physical properties of the object (size, shape and composition) in situ are related to scattered or radiated fields. For whatever purpose, e.g., target identification, radar cross section control, specific radiation waveforms, etc., a basic understanding of the electromagnetic interactions is vital. Our research has shown that a time domain approach provides ideal insight into how such an understanding can be realized. Increasingly, solutions to radiation or scattering problems are sought over broad bandwidths. The canonical response waveforms (co-polarized and cross-polarized response waveforms to impulse, step or ramp excitation) are ideally suited for this purpose because the response to an arbitrary excitation is simply obtained using convolution.

Much of our recent research has stressed the complex natural resonances of a scatterer or radiator, that is, those complex frequencies which ellicit singularities in the transfer function relating excitation and response in a linear system. For distributed parameter systems such as electromagnetic scatterers and radiators, the response to an aperiodic excitation consists of, first, a forced response as the wavefront moves across the body and then a free or natural response as the wavefront moves beyond the body. For fixed time-independent residues, only the free response can be described in terms of the natural oscillation frequencies of the object.

The general goals of our research include:

1) Prediction of scattered and radiated waveforms from objects of increasing complexity for point or plane wave electromagnetic sources with arbitrary waveforms.

2) Investigation of target-dependent excitation waveforms and/or signal processing algorithms to identify and optimize electromagnetic response from specific targets. The K-pulse, whose initial development was done by Professor Emeritus E.M. Kennaugh, is a perfect example of a unique, time-limited interrgating waveform which elicits time-limited and excitation-dependent response waveforms from a target.

3. We seek a more basic understanding of the electromagnetic interactions of complex structures particularly, at the moment, cavity-type structures which admit guided waves. Such understanding will ultimately lead to consideration of K-pulse waveforms for cavity structures.

4. A new compact reflectivity measurement range at the ElectroScience Laboratory (ESL) is presently being used to obtain broadband scattering data on targets of tactical interest. The data which yield the complete polarization scattering matrix are being used in target recognition studies. There is a continuing need, however, for similar data on less complex targets. Accordingly, measurements of certain canonical targets, including simple cavity-type structures, is continuing on this program. Such "complete" data will be used to develop the basic understanding discussed in paragraph 3 above. This research, separately identified as item F, "Transmit Signature Measurements of Radar Targets for Inverse Scattering Research" in the last (1982-1983) program, has now been combined under item E.

A very real measure of the significance of the basic research performed on a program is the transfer of the developed techniques and methods to other less basic programs. The extraction of the complex natural resonances of a target from measured multifrequency scattering data using rational function approximants and the recognition of a target using such resonances in prediction-correlation processing (both concepts developed on this program) are now being extensively tested on another program.* This other program has resulted in a unique new broadband compact range reflectivity measurement facility capable of rapidly measuring the complex polarization scattering matrix of model targets over a 18:1 band (present) with planned extensions to 30:1 band (future) and possibly a 100:1 band (ultimately). This other program (ESL Project 714190) has as one major goal the establishment of prediction-correlation target recognition statistics using complex natural resonances and a realistic data base. Accordingly, no future research on routine extraction of complex natural resonances from measured scattering data nor on application of prediction-correlation processing for target recognition is anticipated on this program. Our research is summarized in the following paragraphs. Written publications and oral presentations are listed at the end of this section. We stress here the fact that we have been extremely active in disseminating our results to the research community.

Accomplishments

1. Complex Natural Resonances and Geometrical Procedures

The K-pulse provides a means of relating surface waves on a structure to the complex natural resonances of the structure [1]. For

*Project 714190, Contract # N00014-82-K-0037 between The Ohio State University Research Foundation and the Department of the Navy, Office of Naval Research, Arlington, Virginia.

solid structures such as spheres, prolate spheroids, circular and elliptical cylinders, etc., the method has been found to be limited only by the geometrical theory of diffraction (GTD) estimate of the attenuation and phase shift of surface rays on the structure [1,2]. That is, the first one or two lowest frequency (natural oscillations) natural resonances predicted are incorrect because the estimates are asymptotic. Higher frequency "pole" estimates are excellent for spheres and circular cylinders and good to adequate for other classical geometries. Therefore, for sufficiently simple solid target geometries a method for obtaining estimates of the complex natural resonances has been delineated. The method itself (circumferential paths) also refutes the idea that the complex natural resonances are simply a mathematical tool and unrelated to the target's physical properties.

For wire structures, results were somewhat less satisfactory except for cases where the wire was very thin (length to diameter ratios (L/D) greater than 1000)[2]. It has been found that for "fatter" wires, improved estimates of the attenuation and excess phase shift of current on the wire are now available [3]. For a straight wire, these formulas yield pole locations with improved estimates of the damping but somewhat poorer estimates of the oscillation frequencies. By properly combining the new and old analytical estimates of attenuation and phase shift, good estimates of the pole locations can now be obtained for both "fat" and "thin" wires. These results are presently being used to modify the analytical estimates of the pole locations of bent wires, curved wire segments, loops and other wire geometries [2]. The delayed technical report [4] on these procedures has now been modified and the report will soon be available for processing. Essentially, a rather lengthy Appendix suggesting alternate procedures has been added.

Related questions concern the frequency-dependent current reflection, transmission and radiation characteristics at wire junctions and the radiative coupling at end points of the wires. The improved estimate of current attenuation and excess phase shift will permit a brief reeximination of these parameters but it is not intended to further delay the technical report on these topics.

2. Complex Natural Resonances Via Rational Function Approximants

A definitive report on the use of rational function approximants to extract complex natural resonances of a target from measured multiple frequency scattering data has been completed.* It has been found that a combination of filtering, windowing, averaging and judicious selection of test frequencies (resonance region) permits a consistent set of

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*The processing methods developed were completed on this contract. Application of the methods and techniques to actual measured scattering data was done on the related contract (ESL Project 714190) mentioned earlier. Target recognition algorithms are being studied on the latter contract.

complex natural resonances (poles) to be extracted from measured scattering data. There are, however, several limitations. These limitations and our conclusions are listed below:

a) The measured data must have an integrated signal to noise ratio of at least 13.5 dB before consistent poles can be extracted. This assumes that the noise is additive. Multiplicative noise remains a moot question.

b) The limitation in a) suggests that in most situations the scattering data for estimating poles must be taken in a controlled environment. This means that target recognition algorithms should <u>not</u> use direct extraction of poles from full scale data. Fortunately, prediction-correlation target recognition does not extract poles directly and is therefore unaffected by this limitation.

c) The extracted pole set for a target, while clearly consistent, does not display precise excitation invariance. Therefore, as a practical matter a geometrically complex target will, for target recognition purposes, have to be considered as several targets, with a set of averaged poles related to a given span of aspects and/or polarizations.*

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*This question is being pursued on ESL project 714190.

d) The report also uses GTD estimates to obtain the creeping wave poles for a thin circular disk geometry. From the results, the K-pulse and response waveform for edge-on incidence for the disk are presented.

No further studies of processing techniques for extracting complex natural resonances from measured scattering or radiation data are anticipated on this contract. We shall, however, continue to explore geometrical and asymptotic procedures, particularly with regard to future K-pulse studies.

3. Transient Current Density Waveforms on a Conducting Sphere

A technical report presenting the transient current waveforms induced on a conducting sphere when illuminated by a plane electromagnetic wave with impulsive time dependence has been published [6]. On the illuminated side of the sphere, the inadequacies of the physical optics approximation in both the E and H planes are illustrated and a simple correction form is suggested. On the shadowed side of the sphere, the changing form of the current density waveforms is discussed and demonstrated. This report demonstrates that first order corrections of the physical optics backscatter approximation are possible even for an object which does not have a depolarized scattering component. This report, with some additional references to research on time domain scattering and radiation performed at the ElectroScience Laboratory, will also be published in a book of NATO Conference Proceedings [7].

4. Cavity Structures

Research on the electromagnetic scattering from finite and open circular waveguide structures is continuing. The ultimate goal is a realistic modeling of the intake and exhaust cavities of jet engine configurations. At the moment, particular emphasis is on the complex natural resonances of such structures and on the K-pulses to be constructed from such complex natural resonances. It should be emphasized that some portions of the research on cavity scattering have been done on other projects.*

While completely consistent results for all aspects of the problem have not yet been obtained, some preliminary results have proved publishable. A paper [8] which demonstrates a technique for using rational function approximations to combine low frequency and high frequency scattering estimates has been accepted for publication by WAVE MOTION. In this case, the low frequency results come from the Wiener-Hopf solution for an open circular waveguide [9] and the high frequency estimates from the asymptotic unified theory of diffraction (UTD) [10]. The targets in this case are finite circular waveguides with various internal (transverse to guide axis) loads. The rational function approximations permit a smooth spanning and transition of the

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spectral range between the lowest cut off frequency for the waveguide (TE_{11} mode) and a higher frequency where the UTD results are apparently valid. Another publication [11] stresses a rational function approximant for extracting complex natural resonances from measured or calculated multiple frequency scattering data. Included here also are estimates of certain of the complex natural resonances of finite and open circular waveguides.

The problem of a finite circular waveguide loaded with a shorted conical structure is currently being studied using a method of moments program for rotationally symmetric scatterers. At present, a portion of the scattered field spectrum is being generated and the poles extracted using a rational function fit approximation. A numerical search procedure will ultimately be added. The new compact range reflectivity facility mentioned in the introduction will materially aid in providing verification data for new cavity scattering results obtained during the next interim.

The (complex natural resonances) poles of a semi-infinite open cylinder have been obtained using a high frequency solution. The poles of a finite open cylinder are being studied to find their relation to semi-infinite geometry. It is noted that the rays bouncing across the rim of a semi-infinite open cylinder, doubly diffracted, triply diffracted, etc., are non-ray optical. Fortunately, they can be decomposed into ray optical components [10]. This is <u>not</u> the Wiener-Hopf solution. The radar cross-section of the open cylinder for on-axis backscattering is given by

$$\frac{\sigma}{\pi a^2}\Bigg|_{\theta=0} = \left| 1 + U_2 \frac{C}{1 - AC} \right|^2 , \qquad \text{(E-1)}$$

where

$$U_2 = -\frac{1}{\sqrt{\pi ka}} e^{-j(2ka-\pi/4)} \qquad \text{(E-2)}$$

$$A = -\frac{e^{-j(2ka-\pi/4)}}{4\sqrt{\pi ka}} , \qquad \text{(E-3)}$$

$$C = 1 + \sum_{n=1}^{\infty} (jB)^n \sqrt{\frac{1}{n+1}} \qquad \text{(E-4)}$$

$$B = -\frac{1}{2} e^{-j2ka} . \qquad \text{(E-5)}$$

It is obvious that the complex frequency roots of $1 - AC = 0$ are the poles of the system. We make the substitution of $Z = jka$, assuming analytic continuity. Equation (E-4) is divergent for complex ka. After some manipulation and employment of the gamma function, Equation (E-4) is converted to an integral form with a removable singularity. At high frequencies, the poles approach

$$S_n = \frac{\ell n 2}{2} + j\,(n + 3/4)\pi \quad n = 0,1,2,\ldots , \qquad \text{(E-6)}$$

in the complex ka plane. It should be emphasized that the low frequency poles are not accurate here.

For the finite cylinder, Pearson [15] and Eftimiu [16] have obtained poles using the impedance matrix (moment method) in the complex frequency domain. Such a method is not used here due to time and computer cost. Instead, the scattering at different angles due to an on-axis incident wave are calculated to produce a frequency spectrum. Poles are then obtained from each spectrum using a rational function fit program. Since the poles of an object are invariant to the angle of excitation and reception, especially here where the impedance matrix (in real ka) is the same for all receiving angles, the poles of each spectrum agree very well. Present research is confined to rotationally symmetric conducting bodies.

A predictable but nonetheless interesting phenomenon is observed in the below first cutoff region of the finite circular waveguide with both ends open or with the rear end closed. The number of poles at frequencies below first cutoff (TE_{11} mode, $(a/\lambda)_{cutoff} = .29305$) is given by

$$N = \frac{(a/\lambda)_{cutoff}}{(1/2L)} + 1 \quad . \tag{E-7}$$

For frequencies below the first cutoff, the backscatter from a cylinder open at both ends and a cylinder with the rear end closed are the same. The above expression has been validated for the cases of L/a = 3.5, 5.5, 7.5, 10. The first term in Equation (E-7) is obviously related to the length of the cylinder. Therefore, these poles are related to rays bouncing back and forth between the front and the rear of the cylinder.

Therefore, these poles are related to rays bouncing back and forth between the front and the rear of the cylinder. The second term of Equation (E-7), a "1", is thought to be related to the bouncing across the rim of the cylinder. The pole which corresponds to this term has its imaginary part (ka) at approximately 1.65 which converts to a diameter of 1/2 wavelength.

To further study these effects, a conically shaped cylinder (a hollow cone with tip cut off) is under investigation. It has the property that it has two rims with different diameter.

A relatively sophisticated model of a jet engine intake geometry was designed and is being built. The model is of no particular jet engine but has representative features common to many intakes. For example, planar rotar and stator blades are canted in opposite directions. The model features a rectangular intake geometry fairing to a circular stator-rotar mount. A major design goal permits individual components to be removed from the model. Measur .ents on the new compact, broadband reflectivity range will yield data spanning the first few cutoff modes of the rectangular aperture. It is felt that the model will yield representative scattering data for an intake geometry. One major feature felt to be too expensive to construct and therefore missing from the model is an actual pitch to the rotar and stator blades. The blades are planar, but canted with respect to the intake axis.

5. K-pulse Studies

The K-pulse waveform as interpreted in the time domain is a unique waveform of minimal duration which, as input to a specified linear system (scatterer or radiator) produces response waveforms of finite duration at all points of interest. Derivations of the input waveform would also possess this property, thus uniqueness requires that the highest order discontinuity be of minimal order as well. It must be recognized that while it would appear that any linear combination of derivatives of finite orders would appear to satisfy the minimal duration test, this process also would introduce new zeros. The further condition that the K-pulse transform zeros match only the system poles must be impressed. The K-pulse for a distributed parameter system can be similarly modified to be the K-pulse for this distributed parameter system and a specified lumped content system without further lengthening.

In a recent paper [12], Pearson purports to show that while the singularity expansion is an ill-suited means for modeling a scatterer's response to a time-limited excitation (since it cannot be made practically useful through truncation), one is mistaken to conclude that it is incorrect or incomplete through this fact. We disagree with this conclusion primarily because of his simplified definition for the Laplace transform of a K-pulse. It is unlikely that this disagreement will be resolved in the near future. We note, however, that two papers [13,14] in the recent literature both demonstrate that there is a nonzero region in the space-time domain where the scattered field cannot be expressed in terms of natural-mode contributions only and where the conventional SEM representation does not hold. One must recognize however, that this result is for a linearly polarized electromagnetic pulse of finite duration incident on a homogeneous or inhomogeneous lossy dielectric slab. Thus, here the target is neither finite nor perfectly conducting.

The question raised by Kennaugh [1] regarding the completeness of the SEM representation has no bearing on the future usefulness of the K-pulse. It remains a unique and powerful tool in identification and imaging and also appears to be useful in antenna studies.*

6. K-pulse for Transmission Lines

Professor Kennaugh had developed the K-pulse concept for various stratified medium or, equivalently, networks formed by cascaded transmission line sections with or without lumped loads. In the limit, it appears possible to extrapolate to the K-pulse for continuously variable media.

Research on the K-pulse has been resumed as unpublished notes and memorandums by the late Professor Kennaugh are being examined. Notes on the subject of the K-pulse for transmission lines by Professor Kennaugh are being studied and investigated. We wish to duplicate results to assure understanding before progressing to other results.

The purpose of this research is to illustrate the application of the K-pulse concept to a class of distributed-parameter systems which

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*See JSEP proposal, Time Domain Studies, for 1983-1984, pp. 77-90.

can be modelled by finite lengths of non-uniform transmission lines. The K-pulse of such a system is the excitation (input) waveform of finite duration which yields response waveforms of finite (minimal) duration at all points of the system. Numerical techniques using a finite element method are developed to derive accurate approximations of the K-pulse and response waveforms for uniform and non-uniform transmission lines. To use the finite element method to analyze a non-uniform line, one first finds the R-matrix which is a matrix related to the right- and left-traveling wave amplitudes at the two ends of a two-port linear system. Then, matrix multiplication is employed to find the resultant N-element approximation of the R-matrix of the continuous line. It is found that each element of the resultant 2 x 2 matrix represents the Laplace transform of a train of equally-spaced pulses with a fixed net duration $T = 2L/C$, where C is the wave velocity on the unloaded line with length L. Finally, these 4 finite duration waveforms are interpreted as canonical waveforms for the distributed parameter system, in the limit as $N \to \infty$.

Some preliminary results for the K-pulse and response waveforms associated with finite transmission lines have been obtained. These results compare well with those presented in Professor Kennaugh's unpublished notes. Work is in progress to study the effect on the K-pulse and response waveforms due to the termination of the transmission lines. Future research will also include a study of the finite element analysis of a line with non-uniform characteristic impedance.

7. Sampling Criteria

An investigation concerning the sampling criteria in wave number space for generating the spatial impulse response of a finite target was undertaken. The impulse response of a finite target is important for target identification and imaging. The other purpose of this investigation is in the management of large amounts of data for potential application for the presentation of scattered field data and for construction of images. The work originates on a different portion of the JSEP program (see reference [17] part F) and carries over into this program. The theory for the foundations of the investigation were completed on the previous program.

Testing of the theory using measured data has been completed. For clarity, only monostatic data of up to two dimensions were considered. The data sets used include: the Mie frequency solution of a metallic sphere situated at the center of a chosen coordinate system; the same metallic sphere situated off the center of the chosen coordinate system; and the GTD frequency solution of a metallic finite circular cylinder. The results agree with the theory closely. The proper choice of canonical confinement for the target in space can greatly reduce the number of samples required to sufficiently characterize the target's spatial impulse response. The investigation was completed with a written technical report [18] which has all the developed programs in Appendices.

8. Interpretation of Transient Signatures

A paper is in preparation on the impulse response of the sphere capped cylinder. The thrust of the paper is to catalogue characteristic waveshapes arising from distinct scattering mechanisms on the target and then relating the mechanisms to target geometry and known spectral behavior. This first paper has branched into a second paper on calibration error on the new compact range. Measurements on the compact range have been made which serve as a standard for the capabilities of the new compact range. From these data, error figures for calibration error on the range have been obtained. The details of these results are given in a technical report [19]. It is estimated that the accuracy of the measurements on the compact range have been increased by an order of magnitude. The circular thin disk has been demonstrated to be an accurate calibration target.

Recent Publications Under Time Domain Studies

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D.L. Moffatt, J.D. Young, A.A. Ksienski, E. Lin and C. Rhoads, "Transient Response Characteristics in Identification and Imaging" in Microwave Imaging Techniques edited by C.K. Chan and T.L. Lim, a series on "Benchmark Papers in Electrical Engineering and Computer Science", edited by John B. Thomas, Hutchinson Ross Publishing Company, Stroudsburg, Pennsylvania, 1984.

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D.L. Moffatt and T.C. Lee, "Time-Dependent Radar Target Signatures Synthesis and Detection of Electromagntics Authenticity Features", presented at NATO Advanced Research Workshop on Inverse Methods in Electromagnetic Imaging, Bad Windsheim, Federal Republic of Germany, September 1983. Invited.

D.L. Moffatt, "Contributions by Professor E.M. Kennaugh to High Resolution Broadband Radar Polarimetry", presented at the Second Workshop on Polarimetric Radar Technology, Huntsville, Alabama, May 1983. Invited.

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